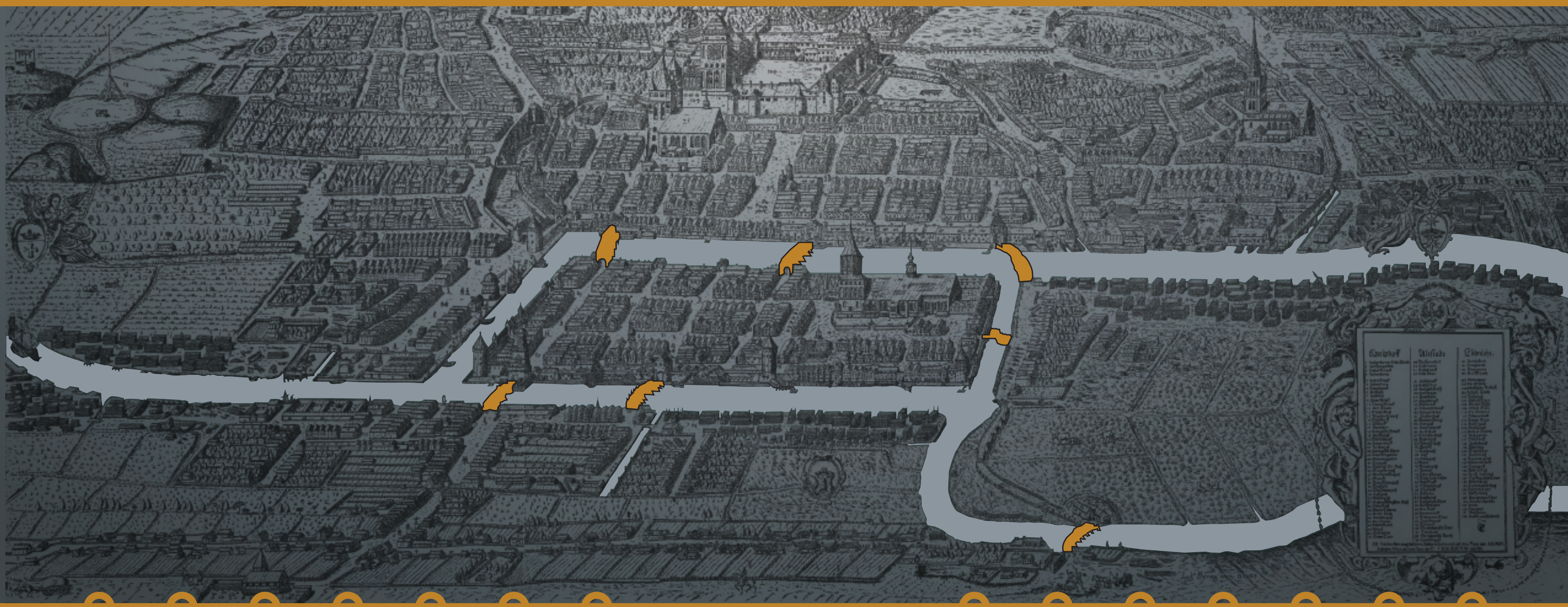

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Advisory Committee for Cyberinfrastructure
Task Force on Campus Bridging

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Members of the National Science Foundation Advisory Committee for Cyberinfrastructure (ACCI) Task Force on Campus Bridging

Craig Stewart (Indiana University), Chair*
Lyle Long (Penn State University)
Guy Almes (Texas A & M University), Co-chair
Clifford Lynch (CNI)
Jim Bottum (Clemson University), Co-chair*
D. Scott McCaulay (Indiana University)
Gary Crane (SURA)
John McGee (Renaissance Computing Institute)
Patrick Dreher (Renaissance Computing Institute)
Michael R. Mundrane (University of California, Berkeley)
Gerald Giraud (Oglala Lakota College)
Jan Odegard (Rice University)
Andrew Grimshaw (University of Virginia)
Jim Pepin (Clemson University)
Sandra Harpole (Mississippi State)
Jim Rice (South Dakota State University)*
Dave Jent (Indiana University)
Larry Smarr (Cal-IT2)
Ken Klingenstein (Internet 2)
Brian Voss (Louisiana State University)
Miron Livny (University of Wisconsin)
Von Welch (formerly NCSA)

* Indicates Task Force members who were members of the NSF Advisory Committee for Cyberinfrastructure during 2009-2010.

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- Office of the CIO of UC Berkeley (http://technology.berkeley.edu/cio/biography.html) for support of the workshop Campus Leadership Engagement in Building a Coherent Campus Cyberinfrastructure, held 11 and 12 October 2010 in Anaheim, CA.
- The home institutions of every Task Force on Campus Bridging member.

Further information about the general topic of campus bridging is available online at http://pti.iu.edu/campusbridging/

Further information about the National Science Foundation Advisory Committee for Cyberinfrastructure (ACCI) is available online at http://www.nsf.gov/od/oci/advisory.jsp

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Case studies

Executive Summary

The mission of the National Science Foundation (NSF) Advisory Committee on Cyberinfrastructure (ACCI) is to advise the NSF as a whole on matters related to vision and strategy regarding cyberinfrastructure (CI) [1]. In early 2009 the ACCI charged six task forces with making recommendations to the NSF in strategic areas of cyberinfrastructure: Campus Bridging; Cyberlearning and Workforce Development; Data and Visualization; Grand Challenges; High Performance Computing (HPC); and Software for Science and Engineering. Each task force was asked to offer advice on the basis of which the NSF would modify existing programs and create new programs. This document is the final, overall report of the Task Force on Campus Bridging.

We used the definition "Cyberinfrastructure consists of computational systems, data and information management, advanced instruments, visualization environments, and people, all linked together by software and advanced networks to improve scholarly productivity and enable knowledge breakthroughs and discoveries not otherwise possible." At the June 2009 meeting of the ACCI [2], the following charge was set for the Task Force on Campus Bridging:

> *The charge of the Task Force on Campus Bridging is to address the broad issues involving improved campus interactions with cyberinfrastructure, broadly construed. It will include a number of different types of bridging:*
>
> - *Campus grids to national infrastructure (both compute and data-oriented approaches) and international CI;*
> - *Campus networks to state, regional, and national;*
> - *Departmental cluster to campus HPC infrastructure; and*
> - *Campus-to-campus and campus-to state/regional resources.*

In other words, the goal of campus bridging is to enable the seamlessly integrated use among: a scientist's or engineer's personal cyberinfrastructure; cyberinfrastructure on the scientist's campus; cyberinfrastructure at other campuses; and cyberinfrastructure at the regional, national, and international levels; so that they all function as if they were proximate to the scientist. When working within the context of a Virtual Organization (VO), the goal of campus bridging is to make the 'virtual' aspect of the organization irrelevant (or helpful) to the work of the VO.

Recognizing that there have already been many excellent reports on the state of US cyberinfrastructure and the need for an educated 21st century workforce in the US, the Task Force on Campus Bridging endorses recommendations relevant to the US open science and engineering research community:

- The recommendations in the report "Leadership under challenge: information technology R&D in a competitive world" [3].
- The recommendation that "the United States should continue to gauge the efficiency of research, measured by the effective uses of research talent and research facilities, which portends the future of a country's innovation environment" which is found in the National Research Council Report, "S&T Strategies of Six Countries: Implications for the United States" [4].

- The recommendations made in the report to the National Academies of Science, "Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5" [5].
- Recommendations regarding networking contained in the December 2010 PCAST report "Designing a digital future: federally funded research and development in networking and information technology" [6].
- Recommendations made in the other five ACCI Task Force final reports [7-11].

Moving beyond these general recommendations, the ACCI Task Force on Campus Bridging engaged in a variety of activities to obtain community input and arrive at findings and recommendations. Members of the Task Force on Campus Bridging hosted three NSF-funded workshops, as follows:

- *Campus Bridging: Networking and Data Centric Issues.* This workshop was held 7 and 8 April 2010 in Indianapolis, Indiana. Position papers were solicited in advance, and 12 were submitted. A total of 45 individuals attended this workshop.
- *Campus Bridging: Software and Software Service Issues.* This workshop was held 26 and 27 August 2010 in Denver, Colorado. Position papers were solicited in advance, and four were submitted. A survey of 5,000 researchers, randomly selected from a pool of 34,623 people classified as principal investigators (PIs) funded by the NSF between 1 January 2005 and 31 December 2009, was also conducted as input into this workshop.
- *Campus Leadership Engagement in Building a Coherent Campus Cyberinfrastructure.* This workshop was held 11 and 12 October 2010 in Anaheim, California. A total of 42 individuals attended this workshop.

With input from a variety of other reports the ACCI Task Force on Campus Bridging arrived at the following findings and recommendations:

Findings

Finding 1: The diversity in the US cyberinfrastructure environment creates tremendous opportunities for US science and engineering research, but adds new types of complexity and new challenges in campus bridging. The cyberinfrastructure environment in the US is now much more complex and varied than the long-useful Branscomb Pyramid. As regards computational facilities, this is largely due to continued improvements in processing power per unit of money and changes in CPU architecture, continued development of volunteer computing systems, and evolution of commercial Infrastructure/Platform/Software as a Service (cloud) facilities. Data management and access facilities and user communities are also increasingly complex, and not necessarily well described by a pyramid.

Finding 2: The reward system as perceived by individual faculty researchers in science and engineering does not support the development of a coordinated national cyberinfrastructure. It encourages a highly diffuse, uncoordinated cyberinfrastructure that makes sharing and collective investment difficult and does not optimize the effectiveness of cyberinfrastructure support for research and development in science and engineering in the United States. In particular, the current reward structure does not align rewards to faculty with a focus on collaboration in ways that support NSF's stated views on Virtual Organizations as an essential organizational structure in scientific and engineering research.

Finding 3: The current state of cyberinfrastructure software and current levels of expert support for use of cyberinfrastructure create barriers in use of the many and varied campus and national cyberinfrastructure facilities. These barriers prevent the US open science and engineering research community from using the existing, open US cyberinfrastructure as effectively and efficiently as possible.

Finding 4: The existing, aggregate, national cyberinfrastructure is not adequate to meet current or future needs of the US open science and engineering research community.

Finding 5: A healthy national cyberinfrastructure ecosystem is essential to US science and engineering research and to US global competitiveness in science and technology. Federal R&D funding overall is not sufficient to meet those needs, and the NSF share of this funding is not sufficient to meet even the needs of basic research in those disciplines that the NSF supports.

Finding 6: Data volumes produced by most new research instrumentation, including that installed at the campus lab level, cannot be supported by most current campus, regional, and national networking facilities. There is a critical need to restructure and upgrade local campus networks to meet these demands.

Recommendations to the National Science Foundation

Strategic Recommendations to the NSF:

Strategic Recommendation to the NSF #1: As part of a strategy of coherence between the NSF and campus cyberinfrastructure and reducing reimplementation of multiple authentication systems, the NSF should encourage the use of the InCommon Federation global federated system by using it in the services it deploys and supports, unless there are specific technical or risk management barriers.

Strategic Recommendation to the NSF #2: The NSF must lead the community in establishing a blueprint for a National Cyberinfrastructure. Components of this leadership should include the following strategic approaches to funding cyberinfrastructure:

- When funding cyberinfrastructure projects that are intended to function as infrastructure, the NSF should use the review criteria and approaches that are generally used for research infrastructure rather than the criteria used for scientific discovery awards. Such awards should be made in ways that complement existing infrastructure and align with best practices, appropriate international standards, and the NSF vision and plans for CIF21.
- The NSF should establish a national cyberinfrastructure software roadmap. Through the Software Infrastructure for Sustained Innovation (SI^2) or other programs, the NSF should seek to systematically fund the creation and ongoing development and support of a suite of critical cyberinfrastructure software that identifies and establishes this roadmap, including

cyberinfrastructure software for authentication and access control; computing cluster management; data movement; data sharing; data, metadata, and provenance management; distributed computation / cycle scavenging; parallel computing libraries; network performance analysis / debugging; VO collaboration; and scientific visualization. Funding for personnel should be a strong portion of such a strategy.

- The NSF should continue to invest in campus cyberinfrastructure through programs such as the Major Research Infrastructure (MRI) program, and do so in ways that achieve goals set in the Cyberinfrastructure Vision for 21st Century Discovery and a national cyberinfrastructure software roadmap.

Strategic Recommendation to the NSF #3: The NSF should create a new program funding high-speed (currently 10 Gbps) connections from campuses to the nearest landing point for a national network backbone. The design of these connections must include support for dynamic network provisioning services and must be engineered to support rapid movement of large scientific data sets.

Strategic Recommendation to the NSF #4: The NSF should fund national facilities for at least short-term storage and management of data to support collaboration, scientific workflows, and remote visualization; management tools should include support for provenance and metadata. As a complement to these facilities and in coordination with the work in Recommendation #3, the NSF should also fund the development of services for bulk movement of scientific data and for high-speed access to distributed data stores. Additionally, efforts in this area should be closely coordinated with emerging campus-level data management investments.

Strategic Recommendation to the NSF #5: The NSF should continue research, development, and delivery of new networking technologies. Research priorities funded by the NSF should include data intensive networks, sensor nets, networking in support of cyberphysical systems, geographically distributed file systems, and technologies to support long distance and international networking.

Strategic Recommendation to the NSF #6: The NSF should fund activities that support the evolution and maturation of cyberinfrastructure through careful analyses of needs (in advance of creating new cyberinfrastructure facilities) and outcomes (during and after the use of cyberinfrastructure facilities). The NSF should establish and fund processes for collecting disciplinary community requirements and planning long-term cyberinfrastructure software roadmaps to support disciplinary community research objectives. The NSF should likewise fund studies of cyberinfrastructure experiences to identify attributes leading to impact, and recommend a set of metrics for the development, deployment, and operation of cyberinfrastructure, including a set of guidelines for how the community should judge cyberinfrastructure technologies in terms of their technology readiness. All NSF-funded cyberinfrastructure implementations should include analysis of effectiveness including formal user surveys. All studies of cyberinfrastructure needs and outcomes, including ongoing studies of existing cyberinfrastructure facilities, should be published in the open, refereed, scholarly literature.

Tactical Recommendations to the NSF:

Tactical Recommendation to the NSF #1:The NSF should fund the TeraGrid eXtreme Digital program, as currently called for in existing solicitations, and should continue to fund and invest in the Open Science Grid.

Tactical recommendation to the NSF #2: The NSF should commission a study of current reward structures and recommendations about the reward structure – particularly as regards promotion and tenure for faculty – that would better align reward structures as perceived by individual faculty members with the type of large, collaborative virtual organizations that the NSF asserts are required for successful approaches to pressing, large scale scientific problems and transformative research.

Tactical Recommendation to the NSF #3: The NSF should support joint efforts with organizations such as the Association for Computing Machinery (ACM), the IEEE Computer Society, and/or Computing Research Association (CRA), to develop and maintain curriculum materials for undergraduate education in computer science and computational and data-driven science and engineering.

In its management of all of these programs, the NSF should make use of the Findings and Recommendations of this report and relevant Task Force on Campus Bridging workshop reports.

Recommendations to university leaders and the US higher education community

Strategic Recommendations to university leaders and the US higher education community:

Strategic Recommendation to university leaders and the US higher education community #1: Institutions of higher education should lead efforts to fund and invest in university-specific, state-centric, and regional cyberinfrastructure – including human resources to support use of cyberinfrastructure – in order to create local benefits in research accomplishments and economic development and to aid the global competitiveness of the US and thus the long-term welfare of US citizens.

Strategic Recommendation to university leaders and the US higher education community #2: Every institution of higher education should have a strategic plan, developed and endorsed at the highest level of its governance, for the establishment of a coherent cyberinfrastructure. Such a plan should have as one of its features a strategy for maximizing effective utilization of the institution's aggregate research cyberinfrastructure and minimizing impact on the global environment. Such a plan should also include ongoing funding for staff to support implementation and use of cyberinfrastructure hardware and software.

Strategic Recommendation to university leaders and the US higher education community #3: Institutions of higher education should adopt criteria for tenure and promotion that reward the range of contributions involved in the production of digital artifacts of scholarship. Such artifacts include widely used data sets, scholarly services delivered online, and software (including robust, widely useable cyberinfrastructure software and other forms of academic contributions). Such an effort must include creation of new ways to provide peer review of these other, newer types of contributions.

Tactical recommendation to university leaders and the US higher education community:

Tactical recommendation to university leaders and the US higher education community #1: Institutions of higher education should continue to press publishers to adopt a strategy of enabling multiple 'primary authors' on research papers particularly so that computer, computational, and informatics scholars can contribute to larger collaborative projects while still being rewarded as primary authors.

Tactical recommendation to university leaders and the US higher education community #2: US colleges and universities should systematically consider inclusion of some costs for research cyberinfrastructure in negotiation of facilities and administration rates. When this is done, the best use of facilities and administration income associated with grant awards to universities will be to use it strategically within the context of a campus cyberinfrastructure plan.

Recommendation to commercial cloud/Infrastructure as a Service (IaaS) providers

Strategic Recommendation to commercial cloud/IaaS providers #1: Commercial Cloud/IaaS providers must work with the US open research community, particularly the community of NSF-funded researchers, to reduce barriers to use of such facilities by the US open research community. Such barriers include technical issues such as the quality of connectivity between the research and education and commercial sectors, business model issues such as transport costs, and policy issues such as the control of geographic location of data for privacy, national security or intellectual property reasons.

Scientific debates have now more importance than ever before for the US and global societies. The place of the US within the global competitive environment is under significant challenge. There are serious concerns about tipping points in the global environment and the ability of the growing human population to live in a fashion we would want for ourselves or for future generations. These are hard, serious problems and the US science and engineering research community should be considering them carefully. It is a critical responsibility of the scientific community to as best possible apply the cyberinfrastructure we have and develop new cyberinfrastructure that aids transformative research, enabling understanding of the world around us and our impact on that world. Investment and leadership by the NSF in technologies related to cyberinfrastructure – and effective actions by the US science and engineering research and education community – can enable more effective campus bridging to facilitate fundamental changes that result in research breakthroughs. To be most valuable, such changes must affect the way research and education are organized – from campus cyberinfrastructure and campus bridging to national cyberinfrastructure, NSF funding strategies, and academic reward systems. These tasks are definitely not the low hanging fruit – but they may be the most important and best fruit and thus should be our focus as a community.

1. Introduction

The mission of the National Science Foundation's (NSF) Advisory Committee for Cyberinfrastructure (ACCI) is to advise the NSF as a whole on matters related to vision and strategy regarding cyberinfrastructure (CI) [1]. In early 2009 the ACCI charged six different task forces with making strategic recommendations to the NSF in important areas of cyberinfrastructure: Campus Bridging; Cyberlearning and Work Force Development; Data and Visualization; Grand Challenges; High Performance Computing (HPC); and Software for Science and Engineering. Each task force was asked to offer advice to the NSF on the basis of which the NSF would modify existing programs and create new programs. This document is the final, overall report of the Task Force on Campus Bridging. It has been endorsed by 21 of the 22 members of the Task Force on Campus Bridging, with no votes in opposition.

In order to define and specify its area of concern, the Task Force on Campus Bridging adopted the following definition for cyberinfrastructure, taken from the EDUCAUSE and CASC (Coalition for Academic Scientific Computing) joint report on campus cyberinfrastructure [12] and Stewart et al. [13]:

> *Cyberinfrastructure consists of computational systems, data and information management, advanced instruments, visualization environments, and people, all linked together by software and advanced networks to improve scholarly productivity and enable knowledge breakthroughs and discoveries not otherwise possible.*

This definition of cyberinfrastructure makes clear that it is a superset of networking and information technology (NIT) as defined in the President's Council of Advisors on Science (PCAST) report "Leadership under challenge: information technology R&D in a competitive world" [3]. This report defines NIT as follows: "'Networking and information technology' comprises the processing and communication of data and information and the hardware, software, and systems that perform those functions." Perhaps because of these related definitions, and in part because of other usages of the term cyberinfrastructure, there is a tendency for people to think first of hardware, and then software, when they think of cyberinfrastructure. Explicit inclusion of the human element as essential to the definition and operation of cyberinfrastructure is intentional, and the recommendations made in this report regarding planning for and funding cyberinfrastructure should be read as inclusive of funding for personnel to operate and support cyberinfrastructure. Because some other usages of the term cyberinfrastructure are not as inclusive in terms of the human element, this report will sometimes point out such issues specifically for emphasis.

At the June 2009 meeting of the ACCI [2], the following charge was set for the Task Force on Campus Bridging:

> *The charge of the Task Force on Campus Bridging is to address the broad issues involving improved campus interactions with cyberinfrastructure, broadly construed. It will include a number of different types of bridging:*
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> - *Campus grids to national infrastructure (both compute and data-orient approaches) and international CI;*
> - *Campus networks to state, regional and national;*

- *Departmental cluster to campus HPC infrastructure; and*
- *Campus-to-campus and campus-to state/regional resources.*

The goal of campus bridging is to enable the seamlessly integrated use among: a scientist's or engineer's personal cyberinfrastructure; cyberinfrastructure on the scientist's campus; cyberinfrastructure at other campuses; and cyberinfrastructure at the regional, national, and international levels; so that they all function as if they were proximate to the scientist. When working within the context of a Virtual Organization (VO), the goal of campus bridging is to make the 'virtual' aspect of the organization irrelevant (or helpful) to the work of the VO. In other words, how do we bridge among different cyberinfrastructures, wherever deployed, to better address the rapidly increasing needs of science and engineering, and empower researchers to use these different CI deployments transparently to make new discoveries?

As a task force charged by the NSF ACCI, the Task Force on Campus Bridging has focused on applications of cyberinfrastructure and needs for campus bridging in research and research education in the NSF-supported science and engineering domains, and the factors affecting campus CI and its optimal use in support of open research and the NSF mission. The NSF has a strong role in US science and engineering, and its mission as stated in the NSF Act of 1950 is "To promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense." [14] Today, federal organizations other than the NSF focus on and fund classified research, including defense research. This report focuses thus on open (nonclassified) research in the science and engineering disciplines currently supported by the NSF. In the most recent NSF strategic plan [15],the NSF organizes its activities according to four strategic goals – discovery, learning, research infrastructure, and stewardship, as set out in Figure 1 below:

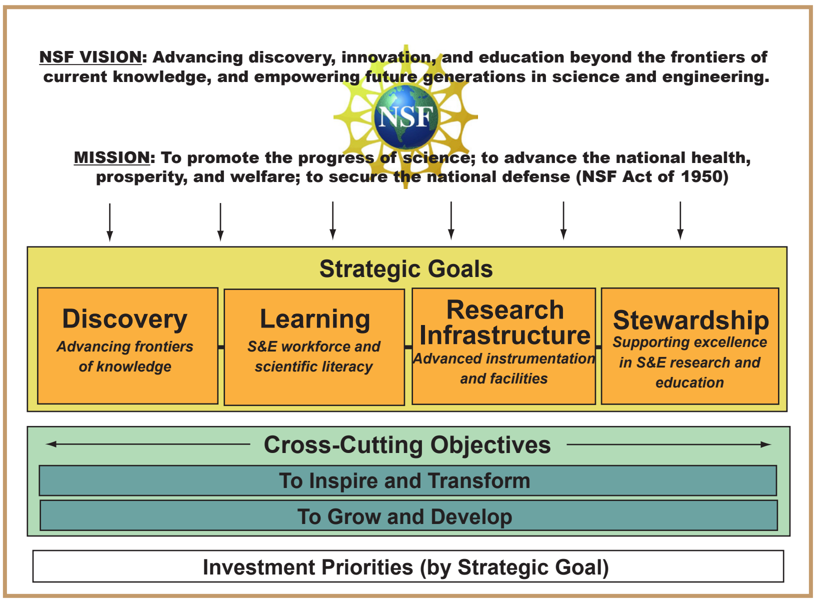

Figure 1. ***Graphical depiction of the NSF vision and mission, including for strategic goals [15].***

While the NSF has a critical role in setting vision, providing leadership, and, through its funding practices, guiding CI implementation and researchers' use thereof, much of the domain relevant to the work of the Task Force on Campus Bridging is outside of direct control of the NSF. Stakeholders and leaders include:

- The US community engaged in science and engineering research, the enablement of which is the ultimate goal of cyberinfrastructure.
- US university and college campus leadership, as decision makers regarding cyberinfrastructure investments made with higher education funds, the authorities who set the reward structures within which researchers operate, and leaders of the institutions that deliver postsecondary education to the people who will make up the 21st century workforce of the US.
- Cyberinfrastructure providers in the public and private sectors, as developers, deliverers, and supporters of cyberinfrastructure used by the US open research community.

The key goal for the Task Force on Campus Bridging is to make recommendations to the NSF, and as appropriate to other key stakeholders, that will result in the optimal use of the nation's aggregate open research cyberinfrastructure and the best possible enhancements of that cyberinfrastructure in order to support the NSF mission [16]. Such recommendations should have as a natural side effect aiding the best interests of the US and worldwide community generally.

There is in this document considerable focus on Virtual Organizations. This focus is driven by the nearly ubiquitous belief in the research community that research should become – and is becoming – more and more collaborative in nature, and that VOs are critical to accelerating research and development and engendering transformative changes in science and engineering [17]. If one accepts a key role for VOs in enhancing US science and engineering (discussed in greater detail in this document in section 2.6), then it follows automatically that it must be possible to bridge from an individual researcher's workstation to a shared cyberinfrastructure used by that VO. To the extent that interesting opportunities or important challenges call for VOs to rapidly be organized and implemented, then it follows that the requisite bridging must be compatible with such rapid and potentially spontaneous VO self-creation.

Further, there was at the outset of the work of the Task Force on Campus Bridging a belief that the total capacity of the national cyberinfrastructure is not adequate to meet the aggregate science and engineering research needs of the US. Campus bridging constitutes one way in which it could become possible to more effectively use the US cyberinfrastructure of today and tomorrow. The need to make the best use possible of existing cyberinfrastructure, and expanding the total capability and capacity of US cyberinfrastructure, is a theme that runs throughout this report.

To address the general matter of campus bridging we must have some way of organizing our views of the national open research cyberinfrastructure and campuses as organizational units.

The Branscomb Pyramid, defined in 1993 [18], is a structure that defines a sense of 'vertical strata' between workstations, campuses, large-scale systems, and leadership class supercomputers and makes implications about the relative abundance of systems of each type. For many years, the Branscomb Pyramid has served as a useful heuristic guide to the structure of the US science and research cyberinfrastructure. As regards the open science community, this was in large part because no entity other than the NSF had the financial capability to fund the systems occupying the pinnacle of the pyramid. Figure 2 illustrates the Branscomb Pyramid circa 2006 as depicted in a talk by Dr. Fran Berman [19].

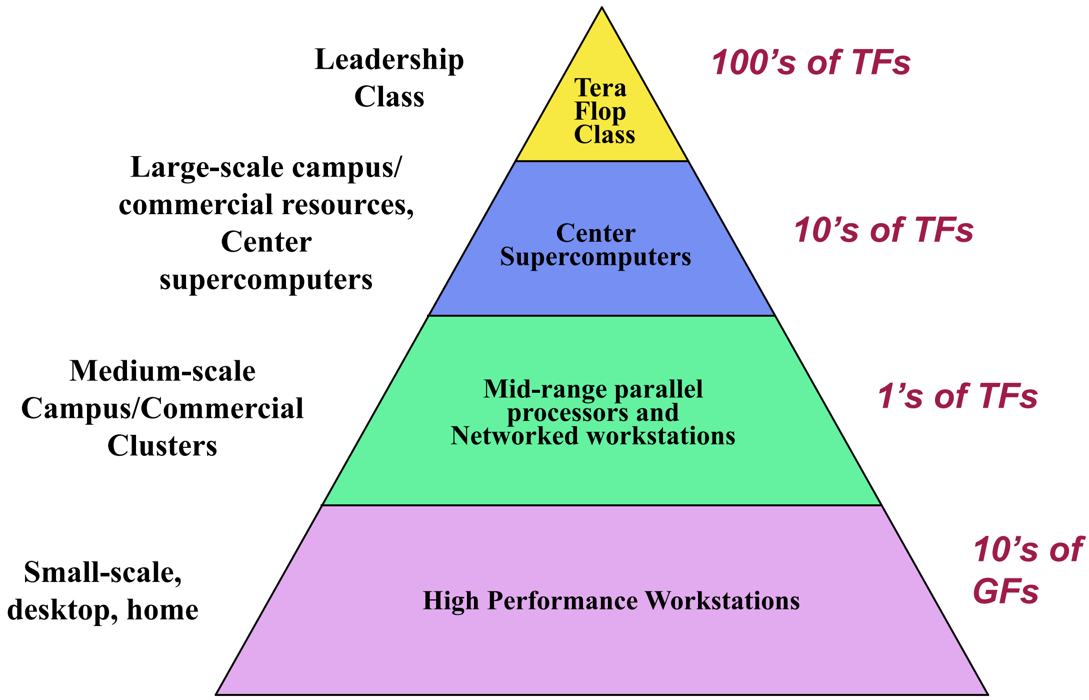

Figure 2. The Branscomb Pyramid, circa 2006, from presentation by Dr. Fran Berman, Director, San Diego Supercomputer Center [19]. (This image by Fran Berman, licensed under the Creative Commons 3.0 unported attribution license [20].)

The national and international cyberinfrastructure systems are much more complicated and have a much greater scale today than when the Branscomb Pyramid was first set out in 1993, as will be discussed in detail in section 2.3. This well understood diagram, however, allows us to orient one aspect of the task of bridging. Bridging must be considered comprehensively from the researcher's desktop to international networks and facilities, across different sizes of systems as depicted in the Branscomb Pyramid. Bridging must also include internationally shared instruments such as the Large Hadron Collider and major telescope facilities. These problems can be organized into two major categories of bridging:

- Interoperability and sharing of similar facilities within a single administrative point of control – such as workstations in a lab or multiple lab clusters within a department. This type of bridging lies primarily within one of the 'strata' of the Branscomb Pyramid.
- Peering among like CI facilities over multiple administrative points of control, or among different and varied CI facilities and multiple points of control. This type of bridging spans CI facilities within one of the strata of the Branscomb Pyramid and across multiple controlling organizations; spans across different strata of the Branscomb Pyramid; and spans also between computational facilities and other types of instruments, often across different geographical regions. The term peering is chosen intentionally by analogy with the concept of peering between/among multiple computer networks [21]. With such networks, while a given routing protocol session runs between two networks, the result of many such pairwise coordinated peerings can be thought of as peering among these networks.

Of the two types of bridging, the simpler is clearly interoperability and sharing of similar facilities within a single administrative point of control. There are a number of effective software solutions that address this task, and the issues are largely matters of deployment, support, acceptance, and compliance within a given organization. As regards peering among like and varied CI facilities over multiple administrative spans of control, there remain tremendous software challenges. This is indeed a critical challenge and no general solutions exist. Most of this document focuses on this 'peering' aspect of campus bridging.

It is also useful to define what we mean by a 'campus.' In general, the physical campus is the unit of organization within which local area networks are built and operated, and it seems sensible to refer loosely to bridging within and between/among campuses without attempting a taxonomy of all existing relationships between university and college administrative structures and campuses. (Ahalt et al. present a listing of common organizational alignments of cyberinfrastructure organizations within universities and colleges [22].) When we speak of a campus we will generally mean just that – a physical campus typically located in one defined physical area, and typically connected by one campus network system that does not involve long haul networks.

1.1. Task force membership, collection of data, and community input

The scope of campus bridging includes a broad space of technical, social, and financial issues. The task force members were selected to represent diverse views and backgrounds. Task force members are listed in Appendix 1. The Task Force on Campus Bridging met regularly via teleconference and several times in person during 2009 and 2010. In addition, the work of the task force was discussed at each of the ACCI meetings held during 2009 and 2010.

The Task Force on Campus Bridging put considerable effort into collecting data and community input. This is because the task force believes that the campus bridging challenge extends broadly throughout this community – far beyond the users of major NSF-supported facilities such as the TeraGrid [23] and the Open Science Grid [24]. Unlike most of the other ACCI task forces, there were no prior reports about the precise topic of campus bridging that could serve as a clear antecedent upon which to build. Much of the motivation for this task force, and in many ways a key starting point for the work of the task force, was the report "Developing a coherent cyberinfrastructure from local campus to national facilities: challenges and strategies" [12] which was the result of a 2008 workshop hosed jointly by the EDUCAUSE Net@EDU Campus Cyberinfrastructure Working Group (CCI) and the Coalition for Academic Scientific Computation (CASC).

As part of the process of obtaining input to create this report, members of the Task Force on Campus Bridging hosted three NSF-funded workshops. Each focused on a particular aspect of the overall campus bridging challenge, as follows:

- *Campus Bridging Technologies Workshop: Networking and Data Centric Issues.* This workshop was held 7 and 8 April 2010 in Indianapolis, Indiana. Position papers were solicited in advance, and 12 were submitted. A total of 45 individuals attended this workshop. Workshop information, including contributed position papers may be found online [25]. The final report from this workshop may be found online [25] and obtained in hardcopy from CreateSpace[1].
- *Campus Bridging Software and Software Service Issues.* This workshop was held 26 and 27 August 2010 in Denver, Colorado. Position papers were solicited in advance, and four were submitted. A survey of 5,000 researchers, randomly selected from a pool of 34,623 people classified as principal investigators (PIs) funded by the NSF between 1 January 2005 and 31 December 2009, was also conducted. (While drawn from the same pool of PIs as the XROADS survey [26], the 5000 invitees were chosen independently of that survey.) A public invitation to take the survey was also posted online. A total of 1,387 people responded to the survey. A total of 32 individuals attended this workshop. Workshop information, including contributed position papers may be found online [27]. The final report from this workshop may be found online [27] and obtained in hardcopy from CreateSpace.
- *Campus Leadership Engagement in Building a Coherent Campus Cyberinfrastructure.* This workshop was held 11 and 12 October 2010 in Anaheim, California. A total of 42 individuals attended this workshop. The final report from this workshop may be found online [28] and obtained in hardcopy from CreateSpace.

Appendices 2-4 present considerable detail on these three workshops, including a list of position papers, their authors, and workshop attendees. The reports from these three workshops constitute the primary inputs informing this report.

During the course of the Task Force on Campus Bridging's work it became clear that a concise technical guide to implementation of authentication with InCommon-based authentication was needed. A proposal was submitted to the NSF to create such a technical guide and was subsequently funded by the NSF. An editorial board of four individuals contributed to and commented on this technical guide. The technical guide is now available online and in print, in both extended and condensed formats [29, 30].

1 See http://pti.iu.edu/campusbridging/ for links to the appropriate web page within CreateSpace to order hardcopies of reports.

Other sources of information regarding national needs for cyberinfrastructure include two reports [26, 31] created as part of a planning grant associated with the TeraGrid eXtreme Digital solicitation [32].

Other NSF reports, NSF-funded workshop reports, and reports sponsored by other federal agencies were also used as sources of input data. The Task Force on Campus Bridging also used current NSF solicitations, particularly the TeraGrid eXtreme Digital solicitation [33], DataNet solicitation [34], SI2 solicitation [35], Major Research Instrumentation (MRI) solicitation [36], and the NSF Cyberinfrastructure Framework for 21st Century Science and Engineering (CF21) [37] as current expressions of need and plans for cyberinfrastructure by the NSF. The last bears particular note in that it calls for a national cyberinfrastructure vision that encompasses:

1. *High end computational, data, visualization and sensor-based systems and the associated user support needed for transformative science; HPC systems and services of all types and flavors, networking, interoperable data systems and mining, including a focus on sustainability and extensibility.*
2. *Activities that link cyberinfrastructure framework into campuses (including government and business) and programs that provide the widely dispersed, most broadly based activities and resources; grids, cloud computing, loosely coupled campus services, federated [identity] management and hybrid networks involving wireless and social networks.*
3. *Major national and international research facilities and collaborations including large-scale NSF collaborative facilities and projects, cyberinfrastructure developed across NSF and other government agencies, including international partners.*
4. *A comprehensive plan for education and outreach in computational science to support learning and workforce development for 21st century science and engineering.*

The development of this framework, now referred to as CIF21, will lead naturally to a holistic and comprehensive vision for a national cyberinfrastructure that builds on prior guidance in important documents such as the 2007 NSF document "Cyberinfrastructure Vision for 21st Century Discovery" [17]. This task force report is written with awareness that the recommendations made should aid the NSF in achieving the goals set for CIF21, particularly items 2 and 4 of the quoted CIF21 vision.

This report is also informed by and carefully aligned with the reports of the five other ACCI task forces. In some cases this report references and endorses recommendations made in other task force reports, rather than including in this report recommendations similar to those included in the reports of other task forces. In general this report takes the approach of referring to and supporting recommendations that are central to the charge of other task forces (e.g. high performance computing systems, data, and human resources).

As part of the process of soliciting community input, a draft copy of this report was made available for community commentary on March 2, 2011. Individuals and institutions were offered the opportunity to submit short comments (anonymously or not) or longer position papers. The period of comment closed on March 16, 2011 for comments that were taken into consideration in the creation of the final version of this report. Additional responses and comments were accepted up till the end of March 2011. The position papers that were submitted as comments on this report are available online [38]. All comments and position papers were made available to the NSF and the NSF ACCI.

All in all, including task force members, position paper authors, individuals who attended workshops, individuals who contributed to the technical report on use of InCommon-based authentication, and individuals who commented on the task force report, a total of 152 distinct individuals contributed to the creation of this report. An additional 1,387 anonymous respondents to surveys also contributed to the data collection that informed this report (there may have been some overlap between these respondents and other identifiable participants in this process). Presentations about this report, while under development, were given at meetings of the following organizations: ACCI, Coalition for Academic Scientific Computation, Internet2, and TeraGrid. The work of this task force was also discussed in panels and Birds of a Feather sessions at the IEEE/ACM SC09 and SC10 conferences. There is thus good reason to believe that the findings presented here are broadly reflective of the US research and research education working in areas of science and engineering currently supported by the NSF.

1.2. Format of findings and recommendations in this report

This report includes a considerable amount of discussion, but the critical elements of the document are *findings* and *recommendations*. Recommendations are subdivided into two types: strategic and tactical. Findings are numbered chronologically, and are important since they represent a particular empirical statement or viewpoint that represents the consensus of the task force at the time of the publication of this report.

The Task Force on Campus Bridging considers and speaks to multiple constituencies. For this reason, we have subdivided our recommendations into three categories:

- Recommendations to the NSF.
- Recommendations to US university and college campus leadership and the US academic research community.
- Recommendations to commercial cyberinfrastructure providers.

These recommendations are presented and numbered within each of the above three categories in the text, and are listed in sequence for each target audience in the executive summary. In the creation of this report, the Task Force on Campus Bridging has focused on a very few recommendations that we view as most important, over the course of the next five to ten years. We hope to make it possible for the NSF and other stakeholders to focus and act on these most strategically important recommendations in the long run, and a very few tactical recommendations in the nearer term. To this end, we have summarized and distilled the essence of a very large number of excellent contributions to the Task Force on Campus Bridging's activities in the form of white papers and discussions at workshops. To anyone interested in the general issues of campus bridging, the task force as a whole commends the workshop reports and contributed position papers as an excellent source of wise viewpoints and valuable suggestions.

1.3. Full listing of reports related to campus bridging activities

Several of the themes discussed by the NSF ACCI Task Force on Campus Bridging were raised in 2008 in a joint report of EDUCAUSE and the Coalition for Academic Scientific Computation (CASC) entitled Developing a Coherent Cyberinfrastructure from Local Campus to National Facilities: Challenges and Strategies [12]. Since early in 2009 when the NSF Office of Cyberinfrastructure introduced the term "campus bridging," there have been a number of workshops and technical reports related to and inspired by the term. In addition to this report, the following workshop reports and technical documents were created with NSF funding, sometimes by individuals who were part of the task force in some form of coordination with the task force, and sometimes without such coordination:

- Report on Campus Bridging Technologies Workshop: Networking and Data Centric Issues [39]
- Report on Campus Bridging Technologies Workshop: Campus Bridging Software and Software Service Issues [40]
- Report on Campus Leadership Engagement in Building a Coherent Campus Cyberinfrastructure [41]
- A Roadmap for Using NSF Cyberinfrastructure with InCommon [29]
- A Roadmap for Using NSF Cyberinfrastructure with InCommon: Abbreviated Version [30]
- Technical Report: Survey of cyberinfrastructure needs and interests of NSF-funded principal investigators [26]
- Technical Report: TeraGrid eXtreme Digital Campus Bridging Requirements Elicitation Meeting [31]

Each of the workshop reports cited above includes copies of all position papers submitted as input to that workshop as well as copies of all PowerPoint slides presented at each workshop. The results of the campus bridging software survey are presented and analyzed as part of the report on Campus Bridging Software and Software Service Issues. Several activities related to the general theme of campus bridging are available online [38]. This web site includes links to position papers submitted as commentary on this present report.

The Task Force on Campus Bridging acknowledges and thanks the many individuals who contributed to its activities over the course of two years of activities. While the task force condensed the material we received in order to focus NSF and stakeholder attention, we believe the workshop reports and position papers constitute a tremendous store of excellent ideas. Included in those works are many suggestions for systems, software, and services that we hope will be submitted to the NSF in the form of grant proposals and be funded by the NSF.

2. Current context – international competitiveness, the changing nature of science and engineering, and the current national cyberinfrastructure

2.1. US competitiveness and the current international context

The worldwide technological environment and US economic situation merit mention in setting context for this report. Reports produced in 2010 reaffirm that US leadership in information technology (IT), and in IT-dependent areas of science and engineering, is under challenge by other countries in ways that are without precedent since the inception of the NSF. Two reports in particular lay out the general challenges: the 2005 report, "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future" [42] and the 2010 follow up report "Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5" [5]. The executive summary of the 2005 report begins:

> *"The United States takes deserved pride in the vitality of its economy, which forms the foundation of our high quality of life, our national security, and our hope that our children and grandchildren will inherit ever greater opportunities."*

It goes on, however, to say:

> *"Although the US economy is doing well today, current trends in each of those criteria indicate that the United States may not fare as well in the future without government intervention. This nation must prepare with great urgency to preserve its strategic and economic security. Because other nations have, and probably will continue to have, the competitive advantage of a low wage structure, the United States must compete by optimizing its knowledge-based resources, particularly in science and technology, and by sustaining the most fertile environment for new and revitalized industries and the well-paying jobs they bring."*

The 2010 report includes a considerably gloomier note, stating that:

> *"The recommendations made five years ago, the highest priority of which was strengthening the public school system and investing in basic scientific research, appears to be as appropriate today as then. The Gathering Storm Committee's overall conclusion is that in spite of the efforts of both those in government and the private sector, the outlook for America to compete for quality jobs has further deteriorated over the past five years."*

Similarly, the President's Council of Advisors on Science and Technology (PCAST) 2007 report "Leadership Under Challenge: Information Technology R&D in a Competitive World" [3] stated:

> *"The United States is today the global leader in networking and information technology (NIT). That leadership is essential to U.S. economic prosperity, security, and quality of life. The Nation's leadership position is the product of its entire NIT ecosystem, including its market position, commercialization system, and higher education and research system."*

The letter of submission within that report, however, notes that:

> *"To maintain – and extend – the Nation's competitive advantages, we must further improve the U.S. NIT ecosystem – the fabric made up of high-quality research and education institutions, an entrepreneurial culture, strong capital markets,*

commercialization pathways, and a skilled NIT workforce that fuels our technological leadership."

A more detailed, and even more sobering, analysis of US global competitiveness is included in the National Research Council (NRC) report "S&T Strategies of Six Countries: Implications for the United States" [4]. This report details the science and technology strategies of Brazil, China, India, Japan, Russia, and Singapore. It lays out in considerable detail the strategies being employed by these countries in their drive toward a position of international leadership in science and technology. Those strategies are at least in some cases bearing fruit. In November of 2010, for the first time in history, a Chinese supercomputer attained the number one position on the Top500 list of the fastest supercomputers in the world [43]. The Chinese Tianhe-1A system at the National Supercomputer Center in Tianjin achieved a peak computation rate of 2.57 PetaFLOPS (a quadrillion – or a thousand trillion – of floating point operations per second) on the High Performance Linpack benchmark [44].

There is much more to advanced cyberinfrastructure than possession of the top spot on the Top500 list, based as it is on just one benchmark application – the Linpack benchmark, which performs a dense matrix linear algebra calculation. Still, this list represents the most easily accessible and widely known measure of investment and capability in massively parallel computer systems. The list is published twice a year, in June and November, with a total of 36 lists issued to date. Of those 36, a US supercomputer was listed in the number one place 25 times. Prior to the November 2010 list, with there were only four supercomputers located outside the US ranked #1 on this list, all in Japan:

- Fujitsu Numerical Wind Tunnel (November 1993, November 1994, and June and November 1995 lists)
- Hitachi SR2201 (June 1996)
- Hitachi CP-PACS (November 1996)
- NEC Earth Simulator (June 2002-June 2004)

The global competitive structure has changed, and a Chinese supercomputer occupying the #1 position on the Top500 list, using technological approaches that have been being pursued by US researchers for some time, is just one indicator. There was a time when a competition among US researchers for funding of a particular type of research would result in funding going to a research team that was also the best in the world at that type of research. This is no longer assured.

The challenges to the US range from accomplishments in current science and engineering activities to preparation of the next generation of scientists and engineers. The reports already cited – particularly the "Rising above the gathering storm" reports [5, 42] – make a compelling case regarding the US educational system and the workforce of the future. An effective, well-trained, inquisitive, and creative 21st century workforce is essential to continued leadership by the United States in science and technology generally and to US global leadership in cyberinfrastructure in particular. An effective national cyberinfrastructure – enabling that workforce to make new discoveries faster, and make discoveries otherwise not possible – is also essential for US global competitiveness.

Recognizing that there have already been many excellent reports on the state of US cyberinfrastructure and the need for an educated 21st century workforce in the US, the Task Force on Campus Bridging endorses recommendations relevant to the US open science and engineering research community and campus bridging:

- The recommendations in the report "Leadership under challenge: information technology R&D in a competitive world" [3].
- The recommendation that "the United States should continue to gauge the efficiency of research, measured by the effective uses of research talent and research facilities, which portends the future of a country's innovation environment" which is found in is found in the National Research Council Report, "S&T Strategies of Six Countries: Implications for the United States" [4].
- The recommendations made in the report to the National Academies of Science, "Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5" [5].
- Recommendations regarding networking contained in the December 2010 PCAST report "Designing a digital future: federally funded research and development in networking and information technology" [6].
- Recommendations made in the other five ACCI Task Force final reports [7-11].

The American Association of Universities (AAU) has made a set of general recommendations to the National Research Council (NRC) Committee on Research Universities [45]. In many cases, specific recommendations made in this report are closely related to recommendations made in general forms by the AAU to the NRC. Such relationships are noted regarding many of the recommendations made in this report.

The economic context surrounding the work of the Task Force on Campus Bridging has changed radically during the two years of task force activity. During that time we have witnessed a far deeper and more persistent recession in the US economy than most experts predicted at the start of 2008. The worldwide economic system has seen a continuing series of crises impacting country after country. The need for advanced cyberinfrastructure in the US as a facilitator of research in science and engineering is now greater than at any time since the founding of the NSF in 1950. The opportunities to expand budgets, however, are more constrained than at any time since the inception of concepts such as *grid computing* and *cyberinfrastructure* and perhaps (in relative terms) since the inception of the NSF. The Task Force on Campus Bridging has thus focused on how best to use existing cyberinfrastructure, existing sources of funding for cyberinfrastructure, and to how most effectively and most cost-effectively make select additional investments to improve US capabilities in cyberinfrastructure.

2.2. The changing nature of science and engineering research

Computer science, computational science, information technology, and cyberinfrastructure are changing science and engineering, at the same time enabling science and engineering to make new discoveries and innovations.

Computational science is now widely recognized as the "third pillar" of science – joining the traditional roles of theory and observation as critical elements of the scientific endeavor [46]. A fourth may now be emerging – data-intensive science [47]. As noted in the ACCI Task Force on Software for Science and Engineering Final Report [9], software has become a way to encapsulate and reproduce expertise and mathematical analysis techniques. As noted in the ACCI Task Force on Data and Visualization Final Report, data sets and their associated metadata are critical records of scientific output and information about our natural world, and many important electronic data sets must be preserved in ways that allow their use into the foreseeable future [8]. There is an important discussion going on in the national cyberinfrastructure community regarding the "third pillar" of computation and "fourth paradigm" of data-centric computing. The overarching importance of both is made clear in the 2010 recommendation by the NSF ACCI, endorsed by then-NSF Director Arden Bement, which identifies computational and data-enabled science as a distinct and important discipline [7]. The science and engineering research community may ultimately arrive at a more felicitous phrase, but for the moment this term is effective in emphasizing the joint importance of computation and data in science and engineering.

For decades the primary organizing structure of the doing of science in academia has been the single investigator and her/his research group. The nature of scientific research and the nature of organizations needed to pursue the most pressing and important problems in science and engineering are changing radically. The following text is drawn from the NSF Advisory Committee for Cyberinfrastructure Task Force on Grand Challenges final report [7]:

> *Virtual organizations connect people across disciplinary, institutional, and geographic boundaries. Cyberinfrastructure can facilitate such connections through communications (e.g., teleconferencing, email), shared resources (e.g., data repositories), and tools (e.g., workflow coordination systems). Cyberinfrastructure can also mediate collaborations by linking observational instruments, data streams, experimental tools, and simulation systems with individuals, who might be alone or in groups, but who as a community are distributed across the globe. Cyberinfrastructure can enable virtual organizations, potentially revolutionizing the way science and engineering are practiced. This is not primarily a technological revolution, although technology makes it possible. It is, rather, a sociotechnical revolution in that it involves representing interlinked social and technical changes in research across all fields of science and engineering.*

Olson et al. [48] present an entire book full of thoughts about and case studies of scientific collaboration on the Internet. They focus on the concept of a collaboratory, a term coined in 1989 by William Wulf [49]. A 1993 National Research Council report [50] recommended the creation of a research program "to further knowledge of how to build, operate, and use collaboratories" in the support of science. A formal definition of collaboratories, based on the outcome of a workshop held at the University of Michigan in 2001, is included in Olson et al. [48]:

> *"A collaboratory is an organizational entity that spans distance, supports rich and recurring human interaction oriented to a common research area, and provides access to data sources, artifacts and tools required to accomplish research tasks."*

Clearly the concept of Virtual Organizations is very much derived from this concept of a collaboratory. The Science of Collaboratories project [51] has fostered significant research about the organization and operation of collaboratories, and as of the writing of this report lists a total of more than 200 scientific collaboratories. There are many publications that discuss the trend toward collaboratories and virtual organizations in academia [48, 52-56]. Olson et al. [52] describe in detail several virtual organizations or collaboratories in a variety of scientific disciplines enabled by cyberinfrastructure. In addition, it must be possible to create or expand the activities of such VOs flexibly and quickly to respond to pressing needs or opportunities. Past examples include the need to create a VO in very short order to react to the outbreak of the SARS virus in 2003 [57], and more recently the creation or expansion of VOs to predict the spread of the H1N1 virus [58, 59] or predict new earthquakes in Japan in 2011. Virtual Organizations must be able to flexibly bring together researchers from many disciplines and many physical campuses. Thus, effective solutions to the problems of campus bridging are of basic importance to the challenges of supporting VOs.

Changes in science and increased importance of VOs are clearly apparent from the ongoing evolution of how science is performed. The NSF's current focus on transformative research seems likely to increase emphasis on Virtual Organizations as essential organizational structures within the NSF-funded research community. Specifically, the NSF has added to its intellectual merit criteria the following: "what extent does the proposed activity suggest and explore creative, original, or potentially transformative concepts?" where transformative is "used to describe a range of endeavors which promise extraordinary outcomes, such as: revolutionizing entire disciplines; creating entirely new fields; or disrupting accepted theories and perspectives — in other words, those endeavors which have the potential to change the way we address challenges in science, engineering, and innovation" [60]. The nature of science and of the organizational structures required to support solving the most important scientific questions of our day are changing, and this must drive changes in the way the US cyberinfrastructure is organized and operated.

2.3. Organization of and demand for cyberinfrastructure in the US

Section 2.3 includes images taken from, and uses data published in, Welch et al. [61]. The images in this document are released under Creative Commons 3.0 Unported Attribution license [20], and the data in this document are released under the Open Data Commons - Public Domain Dedication & License (PDDL) version 1.0. This section of text in this Task Force report should be considered a work derived from Welch et al. 2011, and anyone citing text from this section of this Task Force Report is requested to cite Welch et al. 2011 as well, in keeping with the license terms for that document.

The scope of the challenge considered by the Task Force on Campus Bridging necessarily includes a suite of resources and assets controlled by the National Science Foundation, but also many assets (human, financial, and cyberinfrastructure) not controlled by the NSF. Since the 1993 Branscomb report and the creation of the concept of the Branscomb Pyramid there have been fundamental changes in the type and organization of cyberinfrastructure in the US. There has been a tremendous proliferation of small to modest sized parallel computing clusters, largely enabled by the revolutionary development of Beowulf clustering and subsequent cluster technologies [62]. As a result, individual investigators, labs, departments, schools, and campuses have significant parallel computing resources both in the scale of particular systems and in the aggregate fraction of the national cyberinfrastructure owned and operated by entities other than NSF-funded supercomputer centers. Similarly the expansion of commercial cloud computing providers has fundamentally changed the US and international cyberinfrastructure landscape.

Figure 3 shows a summary of the cyberinfrastructure resources available within the US open research community through the following categories.

- *NSF Track 1*. The anticipated NSF Track 1 system [63] with 10,000 TFLOPS.
- Track 2 and other major facilities. This includes current NSF-funded Track 2 systems and the Open Science Grid, along with other large NSF-funded systems and multi-state consortia (e.g. SURAGrid, DIAGrid) at 3,388 TFLOPS. The value is based on performance numbers in the Top500 list, information provided by the institutions, or estimated from lists of CPUs in such facilities by assuming 5 GFLOPS per core.
- *Campus HPC/Tier 3 systems.* Medium-scale campus clusters and HPC resources at 2,689 TFLOPS. This number was estimated by summing performance numbers for research computing and HPC systems listed at research and educational institutions on the Top500 list, and advertised by Association of American Universities (AAU) and CASC member institutions. Performance for each system was determined preferably by performance information provided by the institutions or by estimation with an assumption of 5 GFLOPS per core.
- *Workstations at Carnegie research universities.* The estimated combined computing capacity of 8,402 TFLOPS from faculty, post-docs, and graduate students assumes that each member of those communities has a 5 GFLOPS personal workstation.
- *Volunteer computing.* The figure of 11,344 TFLOPS is based on statistics provided by contributed computing projects (Folding@Home [64], BOINC [65], GIMP [66]).
- *Commercial cloud (Infrastructure as a Service and Platform as a Service)*. An estimate of 8,643 TFLOPS of commercial cloud computing (Google, Microsoft, Amazon, and Rackspace) capability based on estimates found in blog postings [67-69] with the assumption of 5 GFLOPS per core and, in the case of Amazon's EC2-HPC offering, the Top500 list.

Computational performance alone is not an accurate indicator of computational utility to science and engineering, but these numbers show a pyramid clearly no longer suffices as a diagrammatic representation of the structure of US open research cyberinfrastructure. It is now a common feature of US academic research to have multiple small to moderate computer clusters, distributed within a single campus, each run in isolation under the supervision of an individual principal investigator

(PI), lab, group of labs, department, or other academic unit operating at a level of organizational hierarchy below the college or university as a whole. In addition, any of these entities may choose to obtain cyberinfrastructure services from a variety of private service providers (cloud computing, Software as a Service (SaaS), Platform as a Service (PaaS), Infrastructure as a Service (IaaS), Clusters as a Service (CaaS), etc.). (A useful and up to date definition of cloud computing terms is available from the National Institute of Standards and Technology [70].)

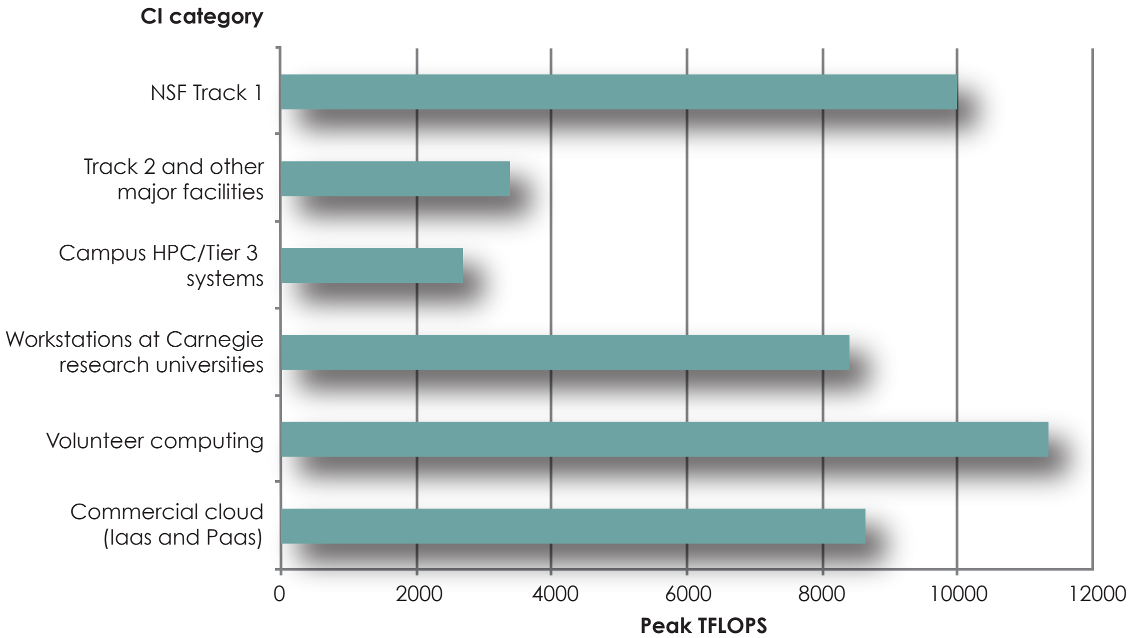

Figure 3. Estimated peak TFLOPS (trillions of floating point operations per second) for major components of national research cyberinfrastructure. This figure reproduced from Welch et al. [61], under Creative Commons 3.0 Unported Attribution license [20].

Figure 3 bears some significant discussion, in part because it depicts a landscape very different from the landscape reasonably well depicted by the Branscomb Pyramid for roughly two decades.

A critical feature of the US national cyberinfrastructure environment today is the tremendous diversity in the types of computing resources that are routinely available to the US research community, including the following:

- Tier 1 at the Petascale. Tightly-coupled supercomputers supporting MPI and MPI-like calculations with a peak theoretical capability of more than 1 PetaFLOPS were first available on the TeraGrid in 2009 [71]. The NCSA Blue Waters system, which will deliver a sustained PetaFLOPS on scientific applications, is scheduled to go online in 2011.
- Tier 2 at 500 TFLOPS to ~ 1 PetaFLOPS. There are a significant number of "Tier 2" systems within the TeraGrid supporting tightly coupled MPI parallel applications as well

as OpenMP/Shared memory systems. These systems generally are in the 500 TFLOPS to roughly 1 PetaFLOPS range.

- Tier 3 in the hundreds of TFLOPS. The November 2010 Top500 list [43] lists 15 parallel computing clusters at US universities and colleges, not part of the TeraGrid and seemingly for use by a single university or college or a collaborative group of universities and colleges.
- Multicore at Tier 4. Apple started shipping dual core processors in its laptops in 2006. As subsequently noted in a talk by Dr. Thomas Sterling at the International Supercomputing Conference in Dresden, Germany, the pervasiveness of multicore processing in everyday laptops dramatically changes the way researchers and software developers have to think about multicore. Single workstations purchased routinely today range from 1 to 24 processor cores and a peak theoretical performance of 2.3 GFLOPS (for less than $500 as of the writing of this report) to 220 GFLOPS. The aggregate personal workstations at the 63 member institutions of the AAU [72] is estimated to exceed 2 PetaFLOPS, while the combined total of all Carnegie research universities is nearly 7 PetaFLOPS.
- Volunteer computing at scale. BOINC is a volunteer computing facility that supports (as of the writing of this report) 37 different research projects. BOINC operates a particular computing environment, and applications have to be ported to run in that environment. Network connectivity to these systems is highly variable and often very limited, but more than 11 PetaFLOPS is a lot of computing power, no matter the limitations of network access to the systems that make up that aggregate.
- Commercial cloud providers.
    - Infrastructure as a Service (IaaS). Infrastructure as a Service is defined as "provision model in which an organization outsources the equipment used to support operations, including storage, hardware, servers and networking components. The service provider owns the equipment and is responsible for housing, running and maintaining it. The client typically pays on a per-use basis." [73]
    - Platform as a Service (PaaS) [74]. There is as of the writing of this report no clear and compelling consensus regarding the definition of PaaS, other than that Google [75] is the biggest existing corporate deliverer of PaaS services. The Google Web Toolkit [76] offers mechanisms by which programmers can develop applications accessible via the Web. The vast majority of existing Google Tools applications are not scientific applications, but scientific applications could well be written in such an environment. Google MapReduce [77] is specifically a tool for analysis of very large data sets and has clear scientific applications [78-80] [81].
    - Software as a Service (SaaS). "Software as a Service (SaaS) is a software distribution model in which applications are hosted by a vendor or service provider and made available to customers over a network…." [82] For example, the statistical package SAS is available via a commercial SaaS service [83]. This type of computing is not listed in Figure 3 because there seems to be no good way to estimate the amount of computing power available for research and engineering purposes. Still, it provides a way to access scientific applications that did not exist in years past.

- o Science and engineering certainly comprise a small fraction of the uses of commercial cloud computing facilities. Still, commercial facilities can very flexibly deliver a very large amount of computing power to a researcher with appropriate limits on his or her credit card and the means to make payments. In total, commercial Infrastructure / Platform / Software as a Service (Cloud) providers now offer more than 8 PetaFLOPS of aggregate computing capability.

In interpreting the data presented above, it should be noted that any attempt to categorize data on the structure of US national cyberinfrastructure is bound to involve some measure of judgment. For example, the aggregate computing capability of workstations of individual faculty, postdoctoral fellows, and research staff at Carnegie research universities was estimated assuming that each such individual has a 5 GFLOPS (millions of floating point operations per section) system as a personal workstation. So that other researchers may work with and reanalyze the data assembled to create Figure 3, those data are available online [61]. One limitation of this data set is that it was impossible to find a comprehensive listing of computational clusters that fall in size between the bottom of the Top500 list and individual workstations. Some data were available through sources such as the Coalition for Academic Scientific Computation [84]. Additional updates to the data underlying Figure 3 as regards clusters in academic research settings that are smaller in computational capability than the bottom of the Top500 list will be valuable in shedding further light on the current status of US research cyberinfrastructure.

It is important to note that TFLOPS alone are no longer an adequate index of suitability of advanced computing resources in support of research in science and engineering. There is indeed a clear and well documented need for petascale and even exascale parallel computing systems [7, 10]. New lists such as the Graph500 [85] and Green500 [86] lists approach different aspects of computational efficiency and effectiveness. Data-intensive computing and data are becoming more and more a focus of attention and central problems in cyberinfrastructure. Approaches to the data deluge may involve very different architectures as suggested by Apache Hadoop [87] and Microsoft Azure [88]. Areas of science ranging from cosmology to genome assembly may require systems with very large memory and relatively modest computational capability, or systems of modest size but which will run continuously for an extended period of time on a particular problem.

It also bears mention that computational capability has been an area of focus in assessing cyberinfrastructure overall in part because the relevant statistics are easy to obtain. There do not yet exist any sources of information about data that are equivalent to the Top500 list. It may not be possible to create such a list, since value and volume of data may not be correlated in the same way that teraflops are correlated with ability to perform calculations and analyses. Fran Berman, in the same talk in which the computationally-oriented Branscomb Pyramid (Figure 2 above) was presented, put forth a data-centric Branscomb Pyramid, shown as Figure 4 below. The issues of scientific data are addressed in greater detail in the report of the ACCI Task Force on Data and Visualization [8] and in a recent special issue of Science [89]. Data-enabled and data-intensive science will become increasingly important aspects of campus bridging as US capabilities in production of digital data continue to expand.

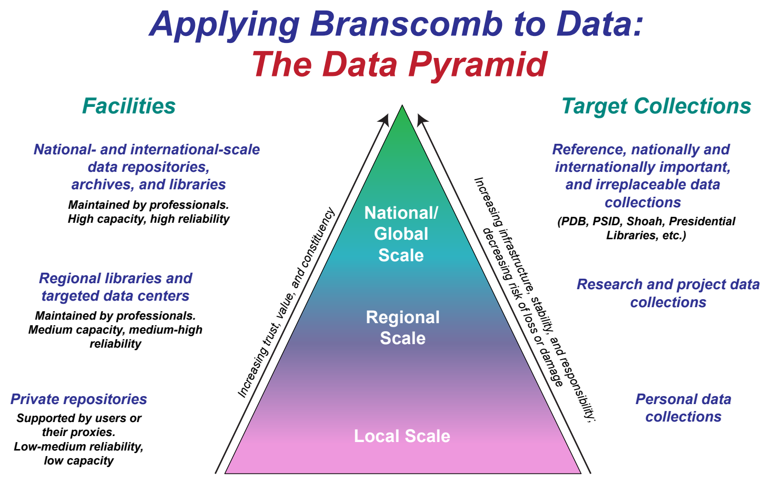

Figure 4. A data pyramid (based on the Branscomb Pyramid) from Dr. Fran Berman, Director, San Diego Supercomputer Center [19]. (This image adapted from a diagram by Fran Berman, licensed under the Creative Commons 3.0 unported attribution license [20].)

It was once believed that the general structure of the Branscomb Pyramid depicted at least in some rough form the number of applications that were able to run effectively at the scale of any particular level of the Pyramid and the number of users who might interact with computational facilities at a given level. This view of the scalability of software applications may well still hold. However, the development of science gateways may require a change in our view of the number of individual users of systems at a particular scale. Science gateways are defined as "a community-developed set of tools, applications, and data that is integrated via a portal or a suite of applications, usually in a graphical user interface, that is further customized to meet the needs of a targeted community" [90]. Science gateways may enable hundreds to thousands of individual users to access computational systems or data sets at the very largest scales in existence [91, 92].

These observations regarding the structure of the US cyberinfrastructure available to the open research community leads to the first finding of the Task Force on Campus Bridging:

> **Finding 1. The diversity in the US cyberinfrastructure environment creates tremendous opportunities for US science and engineering research, but adds new types of complexity and new challenges in campus bridging. The cyberinfrastructure environment in the US is now much more complex and varied than the long-useful Branscomb Pyramid. As regards computational facilities, this is largely due to continued improvements in processing power per unit of money and changes in CPU architecture, continued development of volunteer computing systems, and evolution of commercial Infrastructure/Platform/Software as a Service (cloud) facilities. Data management and access facilities and user communities are also increasingly complex, and not necessarily well described by a pyramid.**

Some discussion of the above finding relative to human resources is important. Perhaps most importantly, the potential value of Infrastructure as a Service approaches to cyberinfrastructure may well offer economies of scale in facilities costs, and in the physical administration of servers up to and including the point of setting up the operating system (in a virtual machine environment or not). However, a very large portion of the overall effort required to support cyberinfrastructure starts at the point an operating system environment is established within which to install and use cyberinfrastructure software (including middleware and application software). In fact, much of the effort required to carry out these tasks may currently be difficult to identify in university and college budgets [93]. To the extent that the expansion of cyberinfrastructure hardware environments becomes more complicated, the personnel required to support these environments effectively may actually increase. This increase may be observable for a time, as options are sorted out and a new equilibrium approach to cyberinfrastructure hardware is established, or the increase in hardware environment diversity may be permanent, and consequently increased personnel requirements may also be permanent.

Another implication of the data in Figure 3, and subsequent discussion has to do with the scale of resources available. In the current CI ecosystem, there are tremendous resources controlled by individual researchers, individual labs, lab groups, or departments. There exists organizational complexity and a tension between researchers' desires for autonomy, self-determination, and effective use of CI at many different levels of organization and the goal of overall effectiveness, efficiency, and capability of the US open research cyberinfrastructure. This complexity and tension is increased by the data deluge, the growing diversity of disciplines making use of advanced cyberinfrastructure, and the technical and financial possibilities of an individual researcher, lab, lab group, or department "owning their own." The following factors are among those that today encourage a highly – and in many cases overly – distributed approach:

- There is value in diversity and flexibility that makes aggregation not the end-all solution. For example, cyberinfrastructure software is still in a rapidly evolving state and it is often much simpler to make N small clusters do N things well than to make one large cluster do N things well simultaneously.
- When a PI controls their own computing cluster, they also control the queue policy. Queue policies on such clusters can boil down to "whatever the PI says should run now, runs now," and such a policy can be valuable in advancing science in the absence of any other mechanism for handling computing needs that are urgent as perceived by a PI. The model of an individual faculty member using a portion of facilities and administration monies returned to them from a grant to create an inefficient and little used cluster that sits idle until that researcher wants to use it is to a certain extent a caricature, but a caricature based at least loosely on a routinely observed pattern.
- Often, utility costs for distributed clusters are without cost to the researcher since campus administration typically pays utility costs for the campus as a whole.
- The academic reward system, including allocation of startup funds for new researchers, and in some cases NSF single-investigator awards, can encourage a researcher to focus

their scope of activities on research problems that can be attacked by a single-investigator research group rather than as a part of a larger virtual organization attacking larger scale, more difficult, and more uncertain problems. Distributed clusters align cyberinfrastructure and its control with the structure of the reward system as perceived by individual faculty members, not necessarily in keeping with the best interests of the US research community or the US society that helps fund such research and expects, over the long term, to receive returns in the form of improved quality of life in exchange for their investment.

In other words, an individual researcher might well rationally decide to use their startup funds to purchase their own cluster to operate in their own lab or department. This, combined with earlier comments on virtual organizations, leads to the following finding:

Finding 2. The reward system as perceived by individual faculty researchers in science and engineering does not support the development of a coordinated national cyberinfrastructure. It encourages a highly diffuse, uncoordinated cyberinfrastructure that makes sharing and collective investment difficult and does not optimize the effectiveness of cyberinfrastructure support for research and development in science and engineering in the United States. In particular, the current reward structure does not align rewards to faculty with a focus on collaboration in ways that support NSF's stated views on Virtual Organizations as an essential organizational structure in scientific and engineering research.

The implications of this finding as regards academic reward structures, and suggestions actions based on it, are considered in detail in Section 7.

While there are many factors that drive the distribution of US cyberinfrastructure resources, the distribution and the current state of software enabling interoperability result in that cyberinfrastructure being used at less than its optimal or maximal effective level. As discussed in detail in the report "Campus Bridging: Software & Software Service Issues Workshop Report" [40], this high degree of distribution of facilities combined with the current state of software results in problems including the following:

- Scientists have difficulty locating resources and services.
- Even when scientists discover services, determining how to use them is a challenge.

This leads to an observation that was one of the driving motivations for the formation of this task force and a statement we record as a formal finding of the task force:

Finding 3. The current state of cyberinfrastructure software and current levels of expert support for use of cyberinfrastructure create barriers in use of the many and varied campus and national cyberinfrastructure facilities. These barriers prevent the US open science and engineering research community from using the existing, open US cyberinfrastructure as effectively and efficiently as possible.

These barriers come from three sources:

- Interoperability and sharing of similar facilities within a single administrative point of control
- Software that may enable, but does not yet make simple or straightforward, peering between like CI facilities over multiple administrative points of control or between different and varied CI facilities and multiple points of control
- An insufficient base of expert human resources to make the best possible use of the existing hardware resources. The key long-term impact on campus CI and campus bridging results from having, supporting, and maintaining the software expertise required to integrate cyberinfrastructure at a variety of levels and deliver optimal support for science and engineering research. There are not sufficient staff available given the current state of cyberinfrastructure software. Nationwide, the investment in staff supporting CI software would be insufficient to support current scientific needs even if cyberinfrastructure software were much more mature than it currently is.

2.4. Current demand for cyberinfrastructure

During 2009 and 2010 two surveys and one focus group meeting were conducted to gauge current demand within the higher education community and community of NSF-funded researchers, as follows:

- A survey regarding needs for and opinions about the current TeraGrid and anticipated TeraGrid eXtreme Digital service, done in the spring of 2010. (This was done as part of needs analysis related to a proposal in response to the TeraGrid eXtreme Digital solicitation and led by individuals involved both in Task Force on Campus Bridging activities and a proposal in response to this solicitation.) A report about this survey is available online [26].
- A survey regarding user experiences with CI, identifying how it is utilized to bridge and which aspects of CI were working well and not as well, done in the summer of 2010. The results of this survey are presented in the Task Force on Campus Bridging Workshop on Software and Services Report [40].
- A small focus group was convened to discuss cyberinfrastructure needs relative to the general topic of campus bridging and the TeraGrid eXtreme Digital program in August of 2009. (This was also done as part of needs analysis related to a proposal in response to the TeraGrid eXtreme Digital solicitation and led by individuals involved both in Task Force on Campus Bridging activities and a proposal in response to this solicitation [31].)

The findings of these needs analyses are summarized in the next sections of this report, along with an analysis of demand for and supply of computing capability within the NSF-funded TeraGrid.

2.4.1. Survey regarding user experiences with CI

Section 2.4.1 includes images taken from, and reuses text and data published in, McGee et al. [40]. This McGee et al. 2011 document is released under Creative Commons 3.0 Unported Attribution license [20]. This section of text in this Task Force report should be considered a work derived from McGee et al. 2011, and anyone citing text from this section of this Task Force Report is requested to cite McGee et al. 2011 as well, in keeping with the license terms for that document.

As part of the Campus Bridging workshop on Software and Services in Denver, a NSF user survey was designed by the workshop organizers and implemented by the Indiana University Center for Survey Research under Indiana University IRB approval. The survey was initiated on August 5, 2010 with an invitation to take the survey sent to 5,000 NSF-funded scientists as well as being made available publicly on the workshop website. The set of 5,000 scientists was randomly selected from a pool of 34,623 people classified as principal investigators funded by the NSF between 1 January 2005 and 31 December 2009. The survey concluded on September 24th, 2010, when a total of 1,387 responses had been collected.

Perhaps the most surprising result is that 722 (53%) of the respondents indicated that they do not use CI beyond their personal workstation or other CI operated by themselves and their team. We believe that at least some of these individuals who responded in this way did not consider the daily usage of networks, community datasets, communication/collaboration mechanisms, etc. as CI. A useful follow-up activity would be to solicit these respondents to take a new survey to better understand this issue.

Figure 5, showing type of CI usage cross-referenced with who operates the CI, indicates that overall CI usage is relatively evenly distributed across the "who operates the CI" dimension.

Figure 6 indicates that data storage, movement, and management are highly concentrated at the individual, local team, and local campus level, with commercial providers coming in significantly less, yet still meaningfully more than "another campus" or national resources. In this data space, state/regional and international are nearly negligible. The commercial CI providers show a significant usage in collaboration tooling, and not surprisingly, the national resources are used most heavily for simulation, data storage, and large-scale data analysis. Outside of the local campus, access to remote instruments was most often accommodated by another campus.

As indicated in Figure 7, the most common method of accessing CI across the entire dimension of providers is via Web browser/portal. With the exception of commercially provided CI, the next most highly used access method across the providers is SSH.

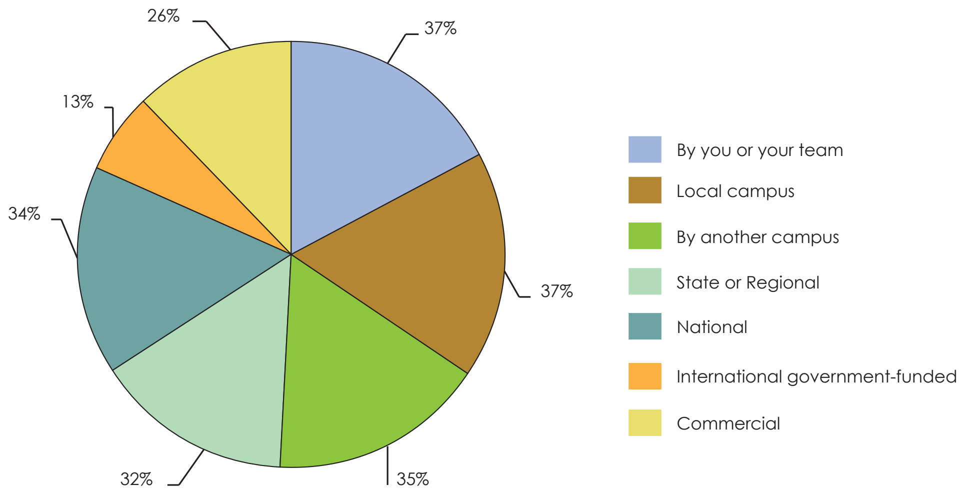

Figure 5. Percentages of respondents who indicated they used CI operated by different types of entities. The total is greater than 100%, indicating respondents who responded that they used CI operated by multiple types of entities. Figure and data from Campus Bridging: Software & Software Service Issues Workshop Report [40], used under Creative Commons 3.0 unported attribution license [20].

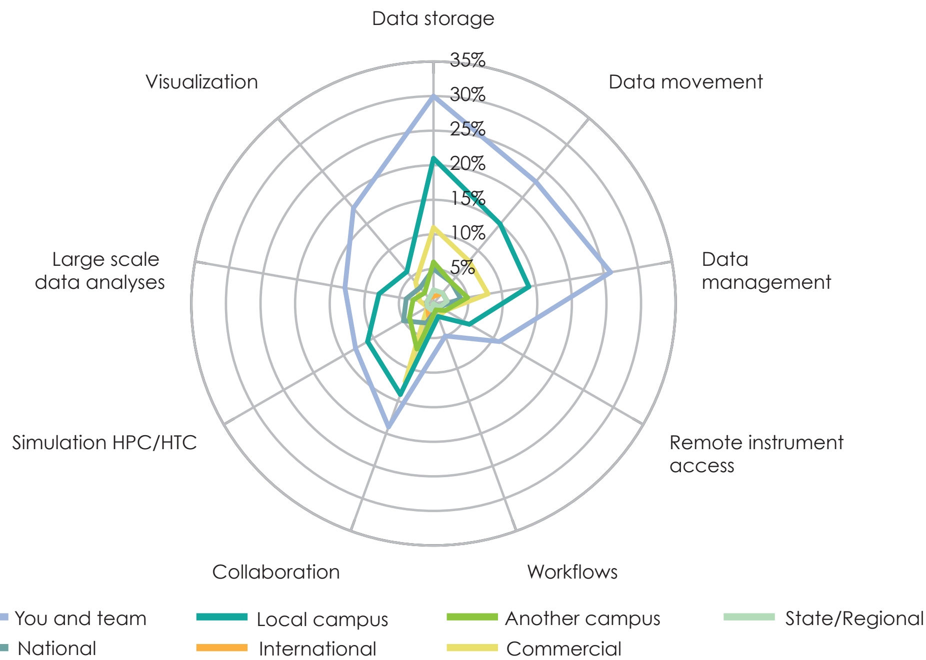

Figure 6. Type of CI cross-referenced by type of operator. The figures shows data storage, movement and management are highly concentrated local to the researchers. Figure and data from Campus Bridging: Software & Software Service Issues Workshop Report [40], used under Creative Commons 3.0 unported attribution license [20].

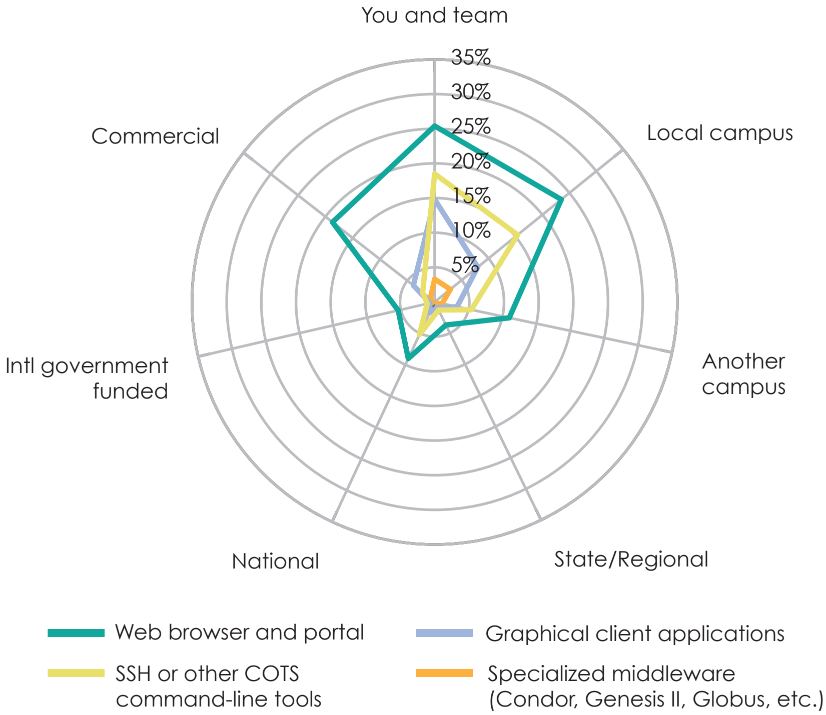

Figure 7. Access method cross-referenced by type of CI operator. The figure shows that Web-based access is most common, followed by SSH except in the commercial space. Figure and data from Campus Bridging: Software & Software Service Issues Workshop Report [40], used under Creative Commons 3.0 unported attribution license [20]

2.4.2. Survey regarding needs for and opinions about the current TeraGrid and anticipated TeraGrid eXtreme Digital service

Section 2.4.2 includes images taken from, and reuses text and data published in, Stewart et al. [26]. This Stewart et al. 2011 document is released under Creative Commons 3.0 Unported Attribution license [20]. This section of text in this Task Force report should be considered a work derived from Stewart et al. 2011, and anyone citing text from this section of this Task Force Report is requested to cite Stewart et al. 2011 as well, in keeping with the license terms for that document.

The NSF solicitation NSF 08-571 "TeraGrid Phase III: eXtreme Digital Resources for Science and Engineering (XD)" [94], issued in 2008, includes the statement, "Over the past three years, the TeraGrid has revolutionized the way in which members of the academic science and engineering community use leading-edge digital resources in their research" and then goes on to say:

> *"The goal of this solicitation is to encourage innovation in the design and implementation of an effective, efficient, increasingly virtualized approach to the provision of high-end digital services – extreme digital services – while ensuring that the infrastructure continues*

to deliver high-quality access for the many researchers and educators that use it in their work. …we refer to the next phase of the TeraGrid as 'eXtreme Digital', 'XD.'"

The solicitation text offers the following in terms of guidance regarding the preparation of proposals:

> *"Key attributes of XD will be that … its design is clearly tied to the user requirements of the science and engineering research community."*

Among the groups submitting proposals in response to solicitation 08-571 was a collaborative team called XROADS, led by University of California San Diego. XROADS prepared a proposal in response to this solicitation under a planning grant funded by the National Science Foundation (award 0928542). As part of its efforts to understand community requirements, the XROADS collaboration carried out a survey of researchers funded as NSF principal investigators from 2005 through 2009 who did not have a TeraGrid account in their own name. The purpose of this survey was to gather information and requirements from researchers who were potential users of the future XD cyberinfrastructure (as defined in the solicitation 08-571 [94]), but whose needs have been elicited from the many surveys of existing TeraGrid users (e.g. [95]). The results of a survey regarding needs for and opinions about the current TeraGrid and anticipated TeraGrid eXtreme Digital (XD) service, done in the spring of 2010, are reported in detail in Stewart et al. [26] and summarized here.

According to searches of the NSF awards database, the NSF funded 35,847 researchers as PIs from 2005 through 2009 inclusive. Of the 34,623 PIs for which survey administrators were able to find functioning email addresses, 1,442 (4.02%) had accounts listed in their own name in the TeraGrid accounts database as of March 2010 (see Figure 8). A survey invitation was sent to a random sample of 5,000 researchers who did not have a TeraGrid account in their own name. More than 20% of invitees responded, and more than 90% of those respondents indicated that their research requires cyberinfrastructure.

The questions in the survey were based on text from the NSF TeraGrid eXtreme Digital solicitation, and the survey results provide a systematic view of the cyberinfrastructure needs of the population of NSF principal investigators who for one reason or another do not use TeraGrid. The survey responses indicate tremendous unmet demand for types of cyberinfrastructure described in the TeraGrid XD solicitation but not available now via TeraGrid, and tremendous need for additional outreach and information dissemination about NSF-funded cyberinfrastructure.

Respondents clearly articulated strong CI needs, including confirmation of the value of large parallel computing systems that are the core of current TeraGrid resources. The survey results also indicated a strong need for more cyberinfrastructure resources – 30.8% of respondents indicated that they 'never' or just 'some of the time' have access to adequate cyberinfrastructure to support their research (see Figure 9). Respondents strongly indicated a need for better services and support for data-centric computing, validating many of the goals in the XD solicitation. Other key themes in responses included: a need for much more information about resources that are available through TeraGrid and/or XD; a need for more information on how to use the resources; a need for a broader array of software than is now available via TeraGrid (particularly support for suites of software relative to specific disciplines, such as Geographical Information Systems, genome science, and mathematical software such as MATLAB[2]); and support for more interactive computing with quicker turn-around.

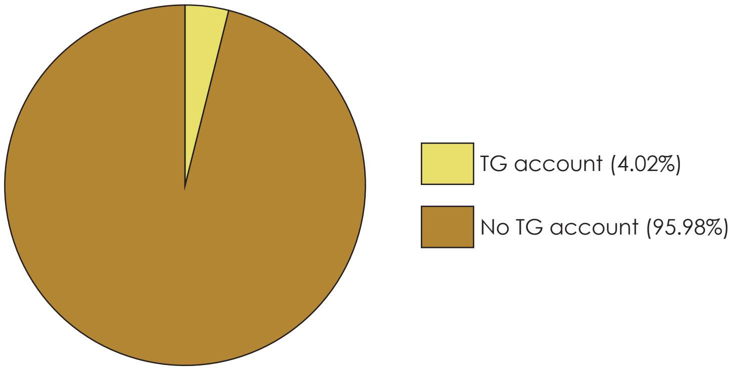

Figure 8. TeraGrid account status of researchers funded as Principal Investigators by the NSF during 2005-2009. Figure and data from Stewart et al. [26], used under Creative Commons 3.0 unported attribution license [20].

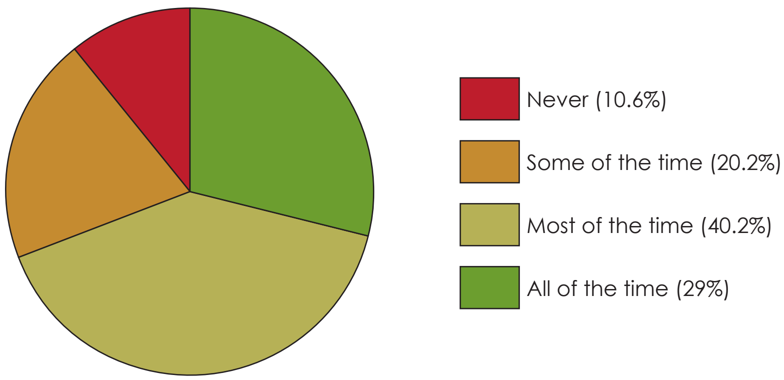

Figure 9. This pie chart depicts the adequacy of access to cyberinfrastructure resources as reported by survey respondents. Yellow, orange, and red segments indicate unmet cyberinfrastructure needs. Figure and data from Stewart et al. [26], used under Creative Commons 3.0 unported attribution license [20].

2 Note that MATLAB is now available on the TeraGrid as an experimental resource supplied by Cornell University, but this was not the case when the survey was in progress.

Further analysis of survey responses indicates a potential group of users for TeraGrid XD that is much greater than current TeraGrid usage – up to 35.84% of all researchers funded as PIs by the NSF between 2005 and 2009. Only a minority – just fewer than 28% of respondents – indicated that they preferred to use only local cyberinfrastructure facilities. In other words, the potential audience of TeraGrid XD users among NSF-funded PIs is roughly four times the potential users of the current TeraGrid and seven times the actual current users of TeraGrid.

2.4.3. Requirements elicitation meeting regarding TeraGrid XD, campus cyberinfrastructure, and campus bridging

Section 2.4.3 includes images taken from, and reuses text and data published in, Stewart et al. [31]. This Stewart et al. 2011 document is released under Creative Commons 3.0 Unported Attribution license [20]. This section of text in this Task Force report should be considered a work derived from Stewart et al. 2011, and anyone citing text from this section of this Task Force Report is requested to cite Stewart et al. 2011 as well, in keeping with the license terms for that document.

In addition to the survey just described, the XROADS collaboration held a series of stakeholder-oriented meetings with scientists, providers, and other future users of the cyberinfrastructure (CI). The meeting goals were to develop a clearer and more functional definition of what the next phase of the TeraGrid should do to effectively deliver services to campuses of US colleges and universities. One of those meetings was on the topic of campus cyberinfrastructure and campus bridging. The results of this requirements elicitation meeting are discussed in detail in Stewart et al. [31] and summarized here. Seven nationally recognized experts spent a day and a half in discussion moderated by an expert in systems engineering requirements identification. Based on responses to a set of questionnaires and discussion by participants at the requirements elicitation meeting, staff involved in the XROADS collaboration arrived at statements of needs regarding TeraGrid XD and campus bridging. Each need is given a criticality level that range from critical to desirable, as follows:

- *Critical.* Multiple participants appeared to indicate that this is essential to their ability to use the system effectively.
- *Highly Desirable.* Multiple participants appeared to indicate that this would enhance their use of the system significantly.
- *Desirable.* Multiple participants appeared to express interest or desire, or one participant indicated that this was essential or highly desirable.

The statements of needs regarding TeraGrid XD and campus bridging resulting from this requirements elicitation meeting are as follows:

- TeraGrid XD overall
    - o TeraGrid XD must create a suite of resources that fill the gap between resources that are feasibly provided at the campus level, and the very large Track I and II systems scheduled to be the vast majority of the TeraGrid by the middle of 2010. Criticality: Critical

- TeraGrid XD must help the NSF occupy a leadership position in cyberinfrastructure within the US and world. Criticality: Highly Desirable
- TeraGrid XD should create a reasonable way for campuses to donate compute resources and in so doing facilitate interoperability between local and national resources. Criticality: Critical
- In order to provide a better, more easily usable system, TeraGrid XD should provide a consistent software environment, and in particular a high-quality scripting environment to support workflows and job management. Criticality: Critical
- In order to provide a better, more easily usable system, TeraGrid XD should provide good mechanisms for interoperability of load between TeraGrid XD and commercial cloud providers. Criticality: Highly Desirable
- TeraGrid XD should have a clear focus that is reasonably balanced between research, discovery, and learning. Criticality: Desirable

- Resources for Training, Education, and Outreach Services (TEOS)
    - TeraGrid XD should create a newsletter that focuses specifically on medium and small schools, to convey information of practical use to them and to demonstrate real interest in broader engagement. Criticality: Critical
    - An Open Science Grid-style of contributed virtual clusters could provide a highly valuable resource for TeraGrid XD TEOS. Criticality: Highly Desirable
- Networking
    - TeraGrid XD must work more actively with the applied networking community, particularly as represented at EDUCAUSE, and look for economically feasible ways to implement dedicated networking where needed by heavy-duty TeraGrid users. TeraGrid XD should have a networking structure fundamentally different than available today – perhaps making some use of dynamic lambda provisioning. The focus of the TeraGrid XD network design has to be on end-to-end solutions valuable to researchers starting at the desktop and going to and through the next generation of the TeraGrid. Criticality: Critical
- Identity management
    - TeraGrid XD should depend upon InCommon and Shibboleth for authentication (or perhaps, more generally, SAML). Criticality: Critical
- Globally accessible file systems
    - TeraGrid XD must include a globally accessible file system and better tools for moving data within TeraGrid XD and between campus systems and TeraGrid XD while protecting as appropriate the security of data. Criticality: Critical
- Advanced support
    - TeraGrid XD should consider embedding consultants (paid for via AUSS) within a very few, very large Virtual Organizations (VOs) – with co-investment of personnel provided by such VOs. Criticality: Highly Desirable

- o TeraGrid XD should offer on-site training [at a major facility of TeraGrid XD]– perhaps with a variety of timing options – one week on site, once per month for 4 months perhaps. Criticality: Desirable
- o TeraGrid XD should establish a certification program, with different levels, including: User, Supporter, Educator, and Domain-Specific certification. Criticality: Highly Desirable
- o TeraGrid XD should provide good online training tools, to ease the challenges to small schools in particular. Criticality: Critical
- o TeraGrid XD should establish a "proposal shepherd" process to aid people through the allocations request process [and improve the allocations request process to boot]. Criticality: Desirable

In addition to the above consensus statements of requirements regarding TeraGrid XD, there was a general and interesting discussion at this REM on the topic of computational science as a discipline. This resulted in the following statement that captures the very strong consensus of the REM participants:

> *Computational Science exists, as a distinct discipline, in addition to and distinct from computer science. The US science and engineering community needs a curriculum for computational sciences that includes problem decomposition, workflows, modeling, rapid prototyping, scalability, and validation and verification.*

This finding is consistent with the recommendation made by the NSF Advisory Committee on Cyberinfrastructure (ACCI) that: "The National Science Foundation should create a program in Computational and Data-Enabled Science and Engineering (CDS&E), based in and coordinated by the NSF Office of Cyberinfrastructure." A copy of the ACCI recommendation, endorsed by then-Director Dr. Arden Bement, is available [7].

2.4.4. Demand and supply for TeraGrid computational resources

The NSF-funded TeraGrid is organized through the collaboration of several organizations and multiple NSF grant awards coordinated by the TeraGrid Forum. The TeraGrid Forum is chaired by John Towns, Director, Persistent Infrastructure, National Center for Supercomputing Applications, University of Illinois. Computational resources within the TeraGrid are allocated through a formal request process, within which a team of experts reviews requests [96]. Computational resources are requested in terms of TeraGrid Service Units, which equal the amount of processing done in one CPU hour in one of the original TeraGrid clusters. A full definition that shows conversion from Linpack results is available [97].

TeraGrid at least largely meets the qualitative needs of its current users, given the generally positive ratings given in surveys of TeraGrid users by the existing TeraGrid organization. Past analyses of researcher satisfaction with the TeraGrid also show a great deal of positive opinions [98, 99]. However, that the community of TeraGrid users desires more resources is verified by reports of the TeraGrid Science Advisory Board (e.g., the report of the 2009 meeting [100]).

For most of the history of the TeraGrid the requests for computational time have greatly exceeded the computational resource available for allocation, so requests are turned into allocations through a process of merit review and adjustment to availability. Towns has for some time maintained graphs of requests for computing time requested vs. awarded; these data are shown in Figure 10. Historically, requests have been about twice the resources available for allocation.

Towns has also developed projections of future demand and supply, extrapolating from past history and based on the following assumptions:

- Multiple resources extended through July 2011.
- Gordon: Data intensive Track 2d resource in second half of 2011 [101].
- Ranger through Feb 2012 [102].
- Kraken through Mar 2012 [103].
- Five resources extended or enhanced through a set of grant awards made to existing RPs through a competitive grant proposal process. These systems are referred to as the 'Dear Colleague Letter' systems as the proposal solicitation was executed via an official NSF 'Dear Colleague Letter' to existing TeraGrid Resource Partners during spring of 2010.
- Does not include potential future resources from Keeneland [104]: presumably not until some time in the second half of 2012.

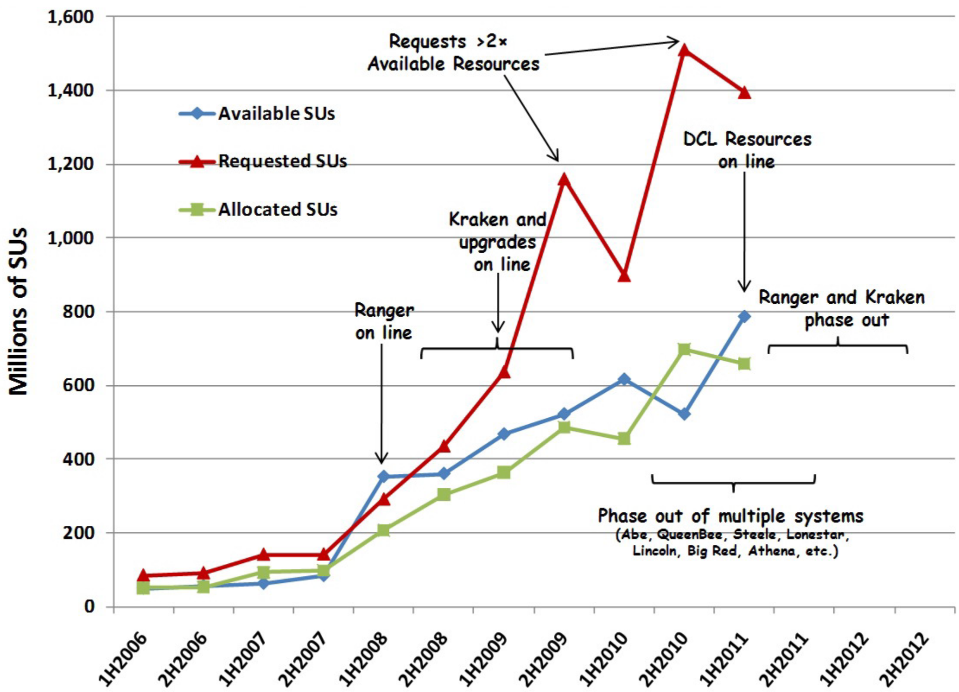

Figure 10. History of computational resources requested and allocated on the NSF-funded TeraGrid. (Data analysis and image provided by John Towns, licensed under the Creative Commons 3.0 unported attribution license [20].)

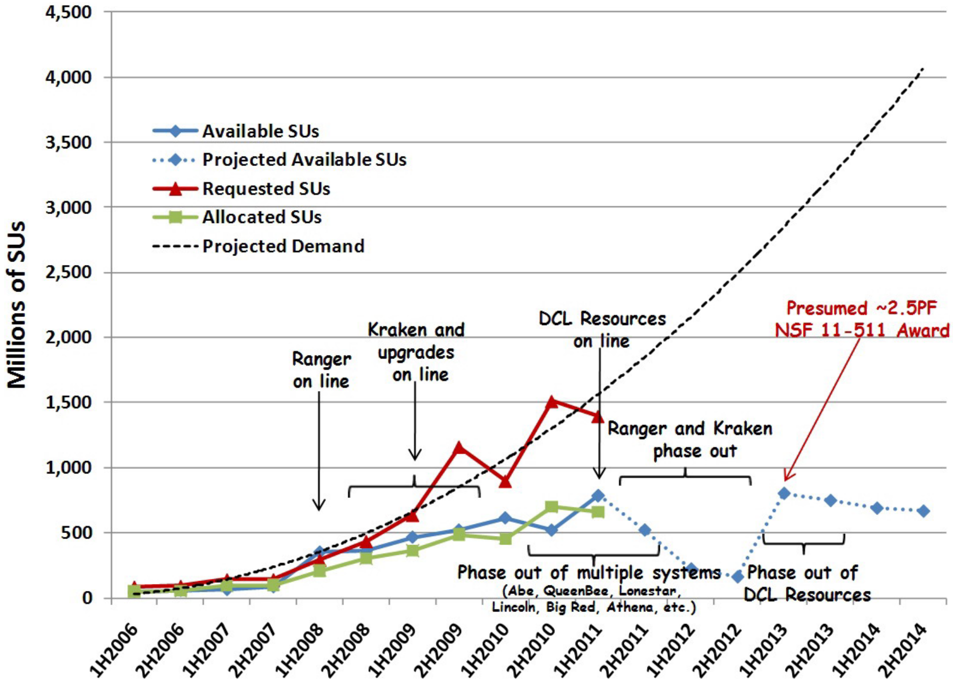

Figure 11. Projected demand and supply for TeraGrid projected from now till 2012. (Data analysis, projections, and image provided by John Towns, licensed under the Creative Commons 3.0 unported attribution license [20].)

New solicitation NSF 11-511 [105] calls for proposals to add a new high performance computing resource to the TeraGrid. NSF solicitation 11-511 states "For the 2011 proposal submission deadline, NSF is interested in receiving innovative proposals for production XD HPC resources capable of at least a petaflop" to be available by January 2012. A projection based on Moore's Law and the scale of the last system acquired through a solicitation like this (the 1 PetaFLOPS Kraken system) suggests, however, that the system acquired through this acquisition is more likely to be on the order of 2.5 PetaFLOPS. With these assumptions, Figure 11 shows projected supply and demand for TeraGrid resources through the end of 2012.

2.4.5. Demand and supply for Open Science Grid computational resources

The report authors requested usage and demand information from the Open Science Grid (OSG) Operations Center. The OSG's response was that while OSG resource demand for 2011 and 2012 has not been officially predicted, a canvas of the eight largest OSG Virtual Organizations (VO) at the beginning of 2010 projected the need for 295 million CPU hours during 2010. Actual usage in 2010 was 347M hours. While individual VO growth is hard to predict, the historical growth of the OSG has been nearly linear from 2007 to 2010. Usage has grown an average of 94M hours per year. Projected, nearly linear growth is displayed in Figure 12.

At present, NSF funding for the Open Science Grid is scheduled to end in 2011.

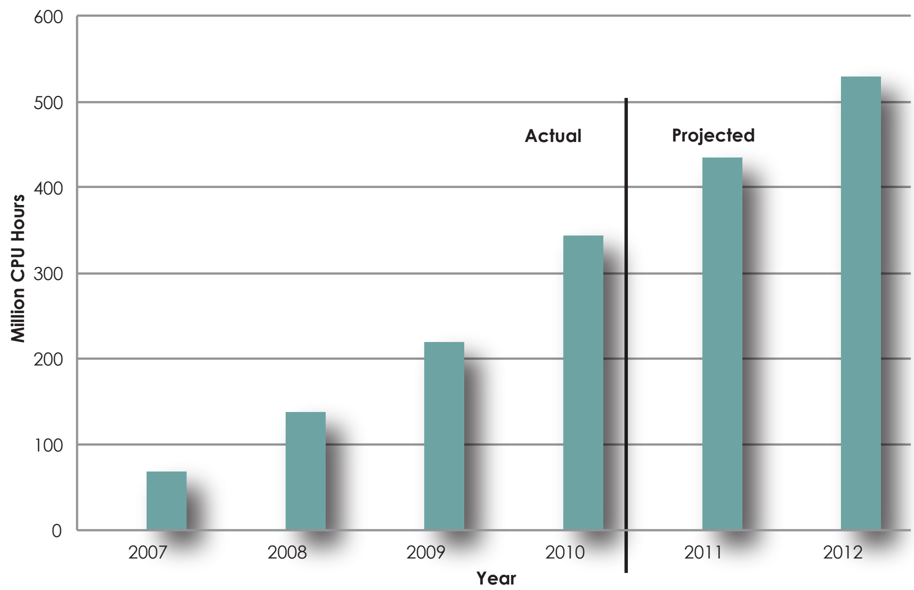

Figure 12. Historical demand for Open Science Grid resources and projections for 2011 and 2012. (Image provided by Robert Quick and James Weichel, licensed under the Creative Commons 3.0 unported attribution license [20].)

2.4.6. US research systems relative to the Top500 list

Section 2.4.6 includes images taken from, and uses data published in, Welch et al. [61].The images in this document are released under Creative Commons 3.0 Unported Attribution license [20], and the data in this document are released under the Open Data Commons - Public Domain Dedication & License (PDDL) version 1.0. This section of text in this Task Force report should be considered a work derived from Welch et al. 2011, and anyone citing text from this section of this Task Force Report is requested to cite Welch et al. 2011 as well, in keeping with the license terms for that document.

Figure 13 shows the top rankings of US systems (overall) and US academic systems within the Top500 list. It shows a clear falloff in the ranking of the top-ranked US system roughly in 2004 through 2007. During this time period some of these top-ranked US systems were put in place with no NSF funding whatsoever. More recently the top-ranked US academic systems have been back closer to the top of the Top500 list, generally being systems resulting from NSF Track II awards. For example, the NICS supercomputer Kraken, which appeared for the first time on the June Top500 list as the 4th-fastest (nonclassified) supercomputer in the world, had a significant impact on availability of computational capability for academic researchers in the US [103]. Figures 14 and 15 together demonstrate that while the aggregate computational capability as represented by the 500 fastest (nonclassified) supercomputers in the world has grown dramatically, the fraction of that aggregate capability represented by US academic research systems has declined slightly, but steadily since 2007.

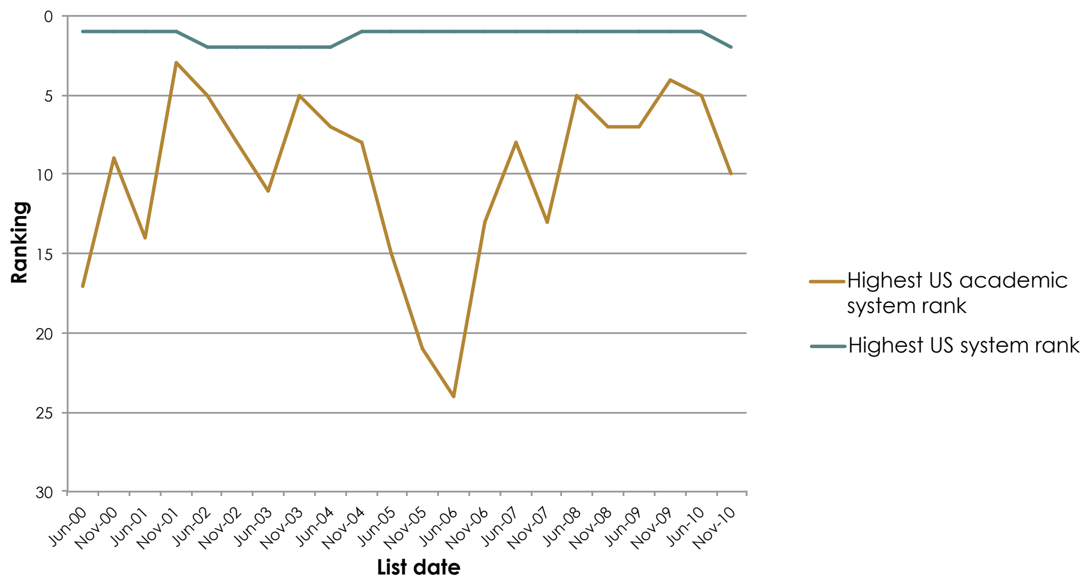

Figure 13. Position of US systems in Top500 list. Figure from Welch et al. [61], used under Creative Commons 3.0 unported attribution license [20]. (Data available from same source under Open Data Commons - Public Domain Dedication & License (PDDL) version 1.0.)

2.4.7. Summary of US national needs for cyberinfrastructure

The information reported here can be summarized briefly as follows:

- Growth in resource availability within the TeraGrid, according to current trends and planned new system additions, is insufficient to continue fulfilling half of the requests for computing time made of the TeraGrid.
- The Open Science Grid is providing significant resources for the US science and engineering community with strong annual growth in demand, but current funding for its operation from the NSF is slated to end in 2011.
- Based on surveys of researchers who did not have their own TeraGrid accounts, there are strong unmet needs for cyberinfrastructure facilities and support.
- Further need for petascale facilities is indicated by the significant community interest in the NSF-funded Blue Waters system being developed at the National Center for Supercomputing Applications (NCSA) [63]. It is anticipated that use of Blue Waters will focus on computing that requires the full scale of that system; it will not be used as if it were a large capacity TeraGrid resource.
- The need for more petascale facilities and exascale facilities is shown in multiple current reports [106-108] and particularly in the ACCI Task Force on Grand Challenges and ACCI Task Force on High Performance Computing reports [7, 10].

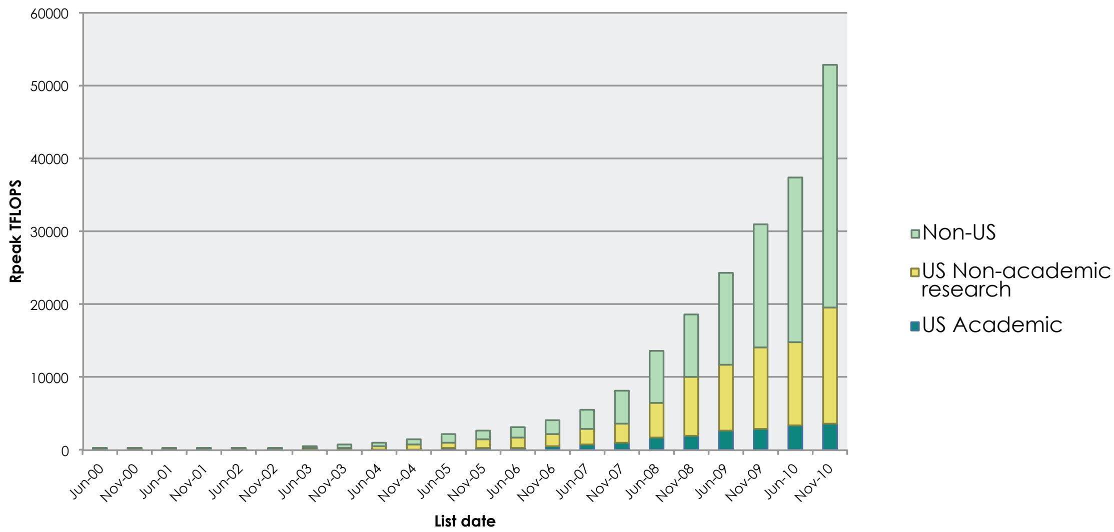

Figure 14. Analysis of systems on Top500 list – aggregate Rpeak of US academic systems, US non-academic systems, and non-US systems. Figure from Welch et al. [61], used under Creative Commons 3.0 unported attribution license [20]. (Data available from same source under Open Data Commons - Public Domain Dedication & License (PDDL) version 1.0.)

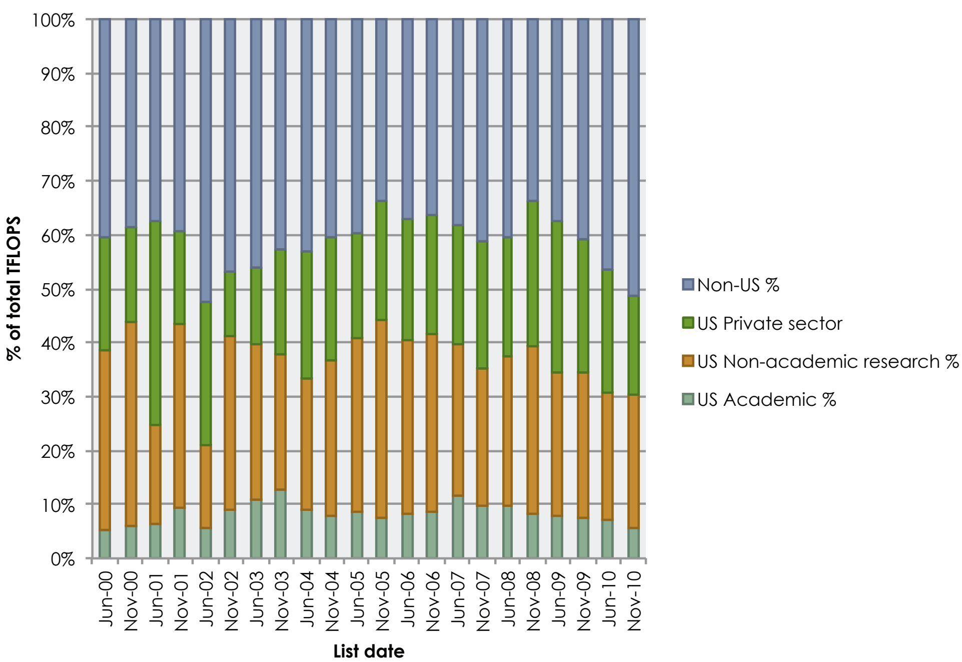

Figure 15. Analysis of systems on Top500 list – aggregate Rpeak of US academic systems, US non-academic systems, and non-US systems, as percentage of total. Figure from Welch et al. [61], used under Creative Commons 3.0 unported attribution license [20]. (Data available from same source under Open Data Commons - Public Domain Dedication & License (PDDL) version 1.0.)

- While earlier in this document we described the tremendous commercial facilities for cloud computing now available if one has the funds to purchase resources, these resources are in practice inaccessible to many US researchers for computing at scale because of cost (this issue is addressed in section 2.3). Furthermore, as described above, such commercial facilities as well as the vast majority of volunteer computing facilities support serial (one CPU) applications well, but do not provide resources appropriate for highly scalable, MPI-style parallel applications.

All of the data collected and cited here lead to an additional finding:

> **Finding 4. The existing, aggregate, national cyberinfrastructure is not adequate to meet current or future needs of the US open science and engineering research community.**

Campus cyberinfrastructure plans as well as national cyberinfrastructure strategies should take into account the opportunities presented by cloud computing. However, based on the data presented in this report, we must make an observation regarding the place of cloud computing in a campus plan, particularly in reference to the recent assertion that 85% of all research computing could be done in a cloud computing environment [109, 110]. It may well be true that 85% of all of the research computing done at one particular institution could be done in a cloud computing environment – particularly if one takes an expansive view of research computing to include use of spreadsheets, word processing, and email in research. However, extrapolating to the entire nation and concluding that this is true nationally is clearly wrong. First, we have in the surveys conducted as part of Task Force on Campus Bridging activities and summarized here clearly demonstrated that the US research community indicates that it does not have sufficient cyberinfrastructure needs. We did not in our own surveys ask what the level of need overall is, nor do we know of any reliable accounting of what the aggregate national needs are. It simply cannot be said at the national level that 85% of the total need for research computing could be done in a cloud environment when there is no good assessment of that the total need is. Furthermore, many of the reports already cited, particularly the ACCI task force reports on High Performance Computing and Grand Challenges [7, 10] talk of the need for large scale parallelism enabled by high speed interconnects. In a careful comparison of Amazon's Elastic Compute Cloud (EC2) and NCSA's Abe supercomputer (then available through the TeraGrid), using the NAS benchmark suite, Walker found that 'a performance gap exists between performing HPC computations on a traditional scientific cluster and on an EC2 provisioned scientific cluster.' [111] A 2010 paper [112] reached similar conclusions. Amazon is just now beginning to support high speed interconnects supporting MPI-style parallel computing [113]. While as noted above cloud computing has important roles in science and engineering computing, it does not seem sensible to assert that in general 85% of research computing can be done in cloud environments. What is clear, however, is that overall the US clearly has unmet needs for cyberinfrastructure, and yet US cyberinfrastructure facilities that are not deployed in the most effective manner or used to the maximal possible effectiveness. The US higher education community and the NSF both have important opportunities to improve this situation.

2.5. US cyberinfrastructure as an ecosystem problem

It has been often noted that US cyberinfrastructure can be viewed as an ecosystem. Among the reports notably making that case is the 2005 report of the President's Information Technology Advisory Committee [46]. It seems useful to draw on biological insights regarding ecosystem diversity, stability, and health. The Shannon Weaver index of biodiversity [114] was an early way to assess the diversity of ecosystems:

where pi is the relative abundance of each species (as measured by the number of individuals of a particular species relative to the total number of species in a community or ecosystem). In general, the higher the number of species in an ecosystem, and the more evenly they are represented, the more stable the ecosystem. For example, it seems intuitively obvious that a field of one variety of corn is less stable than a Brazilian forest. There are limits of course; an ecosystem with as many grizzly bears as field mice would not be particularly stable. And we note that the area of biodiversity studies is much more sophisticated and advanced than the brief sketch given here. But as a rough analog, the idea that variety of species and equitable representation of different species brings ecosystem stability and health is instructive. Certainly the consolidation of control and risk in a very small number of very large financial institutions and the resulting recent near collapse of the US economy in the past two to three years provides a good example of the fragility of an ecosystem lacking in diversity.

The US cyberinfrastructure ecosystem health is now under significant challenge. Intuitively, it certainly appears that the national cyberinfrastructure community is decreasing in diversity. (Thus far it has not been possible to obtain the data required to do a formal diversity analysis using tools such as the Shannon Weaver or other diversity indices; such a study may well be informative and useful.) A recent NSF-funded workshop focused on the challenge of developing sustainable funding and business models for high performance computing centers [115]. The final report of this workshop stated "workshop participants represented a broad spectrum of cyberinfrastructure facilities, ranging from the largest national centers to very small facilities just being formed, the

$$H' = -\sum_{i=1}^{S}(p_i \ln p_i)$$

primary focus of the workshop was on small to medium-sized CI facilities. The recent economic downturn has presented significant funding and organizational challenges to these facilities, calling into question their long term sustainability" [115]. Federal and state budgets are under extreme pressure, leading to diminished levels of service and activity particularly at cyberinfrastructure centers that are focused on service at the state level [22, 115]. Nationwide there are significant pressures at the level of individual institutions of higher education [115, 116].

The NSF budget, however, cannot solve this problem on behalf of the nation and its institutions of higher education. Just as the NSF funds a small fraction of buildings and other infrastructure on most campuses, campus leadership must expect that the NSF or other federal agencies can fund a small fraction of the cyberinfrastructure needed on campus for research and research education.

Universities, colleges, and their leadership must recognize that institutional investment in cyberinfrastructure is a critical aspect of the success of any research or research education institution and organization. (This discussion of US cyberinfrastructure in terms of ecosystem diversity was initially presented as part of a panel discussion at SC2011 [117].)

This leads to a finding, a recommendation, and an endorsement of recommendations in other ACCI task force reports:

> **Finding 5. A healthy national cyberinfrastructure ecosystem is essential to US open science and engineering research and to US global competitiveness in science and technology. Federal R&D funding overall is not sufficient to meet those needs, and the NSF share of this funding is not sufficient to meet even the needs of basic research in those disciplines that NSF supports.**

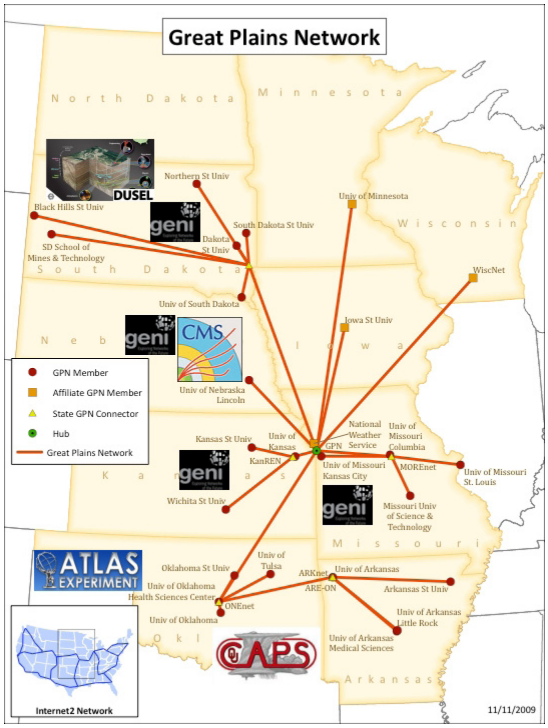

Figure 16. Members of the Great Plains Network Consortium visualize the network's role in support of research and education projects that utilize advanced cyberinfrastructure. (Image provided by Greg Monaco, licensed under the Creative Commons 3.0 unported attribution license [20].)

Because state-oriented and regional cyberinfrastructure facilities are almost exclusively organized and operated by universities and colleges, at least in terms of the open research community, the following recommendation is made to academic leaders and the academic community, although it calls for action by other entities (particularly state governments) for its implementation:

> *Strategic Recommendation to university leaders and the US higher education community #1: Institutions of higher education should lead efforts to fund and invest in university-specific, state-centric, and regional cyberinfrastructure – including human resources to support use of cyberinfrastructure – in order to create local benefits in research accomplishments and economic development and to aid the global competitiveness of the US and thus the long-term welfare of US citizens.*

This recommendation is more specific than but completely consistent with recommendations made to research universities and states by the AAU. As regards recommendations to states, the AAU recommends that states "enhance the role of state funding and create incentives" in support

Figure 17. The TeraGrid is one of the largest open science facilities in the US. Image courtesy of Indiana University, based on illustration by Nicolle Rager Fuller, National Science Foundation.

of public research universities, and that states should "consider higher education funding as an investment." As regards research universities, the AAU recommends that such universities address costs through a variety of means including "increased regional collaboration among research universities" [45]. This recommendation is also consistent with a recommendation made in the report of an NSF-funded workshop on campus bridging issues related to networks and data – that universities strive to adopt a model for state or regional cyberinfrastructure that is based, at least in part, on the demonstrated success of Regional Optical Networks [39]. The NSF CIF21 initiative will lead naturally to a holistic and comprehensive vision for a national cyberinfrastructure. As part of the process of defining the specific elements of that vision, the Task Force on Campus Bridging endorses suggestions regarding scale of investment in and the long-term stability of advanced cyberinfrastructure and HPC centers made in other ACCI task force reports.

In the shorter term, the NSF clearly recognizes the need for additional national computing resources, through recent awards to add facilities to the TeraGrid [118-122] and through a new solicitation for acquisition of high performance computing systems [105]. These steps will be of significant aid to US researchers with high performance and parallel computing needs. The Open Science Grid (OSG) has for several years been the major NSF-funded facility supporting high throughput computing. Indeed, the OSG is an exemplar of excellence in campus bridging, involving as it does computing facilities specifically funded to address particular science tasks best met through high throughput computing approaches (e.g., analysis of data from the Large Hadron Collider), volunteer systems, a span of resources that is international in scope, and a management and support structure that is based explicitly on Virtual Organizations [123]. The NSF included a solicitation for High Throughput Computing (HTC) facilities as part of solicitation 08-573 [124], but did not make an award for such a facility. There are not at present any solicitations released for support of HTC facilities. HTC is an important part of the US cyberinfrastructure ecosystem. It is clearly established that there are several classes of science and engineering research problems that are well addressed with an HTC approach, and that CI facilities supporting HTC do not require the extensive investment in high-speed interconnects that characterizes the large scale TeraGrid facilities and the NCSA Blue Waters petascale system. The Task Force on Campus Bridging thus makes the following tactical recommendation:

Tactical Recommendation to the NSF #1: The NSF should fund the TeraGrid eXtreme Digital program, as currently called for in existing solicitations, and should continue to fund and invest in the Open Science Grid.

Acting on this recommendation is an important step the NSF can take to support the overall CI ecosystem in the US. This is a very specific instance of a recommendation made generally by the AAU – that the federal government "increase support for facilities and equipment" [45].

2.6. Campus and national organization of cyberinfrastructure

Section 2.6 reuses text published in Dreher et al._[41] and Almes et al. [39]. These two documents are released under Creative Commons 3.0 Unported Attribution license [20]. This section of text in this Task Force report should be considered a work derived from Dreher et al. 2011 and Almes et al. 2011, and anyone citing text from this section of this Task Force Report is requested to cite Dreher et al. 2011 and Almes et al. 2011 as well, in keeping with the license terms for those documents.

Much of the overall national cyberinfrastructure is controlled at the campus level. There are several factors that will or could drive significant movement toward more effective and better coordinated cyberinfrastructure at a campus level. In particular:

- Many distributed clusters use more energy – producing more CO2 as a result if the energy source is based on carbon use – and use human resources less effectively than large centralized clusters [93]. Similarly, distributed clusters tend to be less useful and less effectively used as they age. Clusters purchased with start-up funds seem particularly difficult to maintain effectively as systems age and becomes obsolete or excessively prone to hardware failures.
- Many distributed clusters sit idle when not in use by their primary owners, because there is either insufficient staff available to implement existing cycle sharing technologies (e.g., Condor [125]), there is a lack of awareness of how straightforward such technologies are now, or the types of computing supported by such technologies do not match the computing needs of researchers who might use remote clusters when they are otherwise idle.
- Coordination of campus cyberinfrastructure provisioning and support with other CI at other campuses and the state, national, and international levels represents a significant benefit in terms of that CI being more effective for producing both research benefits and economies of scale [126, 127]. These advantages in the economies of scale can be employed to react effectively to the current overall economic challenges facing the US and the world.
- We are at a 'once in 20 years' phase transition in CI driven by new data creation capabilities, the resultant exploding growth rates of data and networking capabilities, and the requirement for science to become increasingly collaborative and interdisciplinary in order to address the most challenging science and engineering problems [39].

High Throughput Computing at University of Wisconsin-Madison

Over the last several decades research across many disciplines has seen a growing importance of cyberinfrastructure (CI), and in several dimensions: High Performance Computing (HPC), High Throughput Computing (HTC), high speed networks, massive data storage and management, and specialized applications ranging from computational optics to atmospheric sensing. The University of Wisconsin-Madison (UW) has a long history of moving from local instances of CI to more coordinated distributed systems. The most successful example of this is HTC enabled by the UW-developed Condor technologies (http://www.cs.wisc.edu/condor/).

There is a power law relationship in national HTC resources as one moves from individual UW-Madison researcher resources (of which there are tens of thousands), through larger local groups such as UW's NSF-funded Materials Research Science & Engineering Center (of which there are thousands) to international scale projects like IceCube and UW-Madison Space Science and Engineering Center (SSEC) (of which there are hundreds), and finally to entities such as the UW Center for High Throughput Computing (CHTC). CHTC not only makes available its own central CI resources to researchers, it also provides services and software tools that enable the UW community to run HTC applications that harness the distributed computing power of many of the campus's distributed HTC resources.

Today, close to 10,000 cores and more than 2 petabytes of disk capacity across the UW campus are organized as heavily utilized Condor pools. A state-of-the-art, rapidly evolving campus network operated by the Division of Information Technology (DoIT) connects these pools. The network provides high-speed connectivity to a fully redundant Ethernet backbone. The backbone spans three supernodes, 12 nodes, and approximately 160 radial buildings. Communication speeds are 20 Gbps between supernodes and a minimum of 1 Gbps between nodes, radials, and telecommunication rooms. Five of the buildings on the campus are connected trough 10Gbps or faster links.

As an international leader in the development and adoption of CI frameworks and tools, the Open Science Grid (OSG) provides access to HTC resources owned by 10 different UW campus entities. These resources are organized locally as the Grid Laboratory of Wisconsin (GLOW) and recognized as an OSG Virtual Organization (VO). UW researchers who are GLOW members can access CHTC services to transparently harness opportunistic resources on OSG. For example, GLOW supports the HTC activities of two UW Large Hadron Collider (LHC) research groups. These two groups are one of the main users of the wide area networking capabilities of the UW campus. The UW campus can sustain high transfer rates through its OmniPop connections to NASA, CERN, ESnet, and to Internet2 via the WiscREN cooperative networking effort of UW-Madison, UW-Milwaukee, and WiscNet, who share the costs of providing high-speed research network access to their users. In some cases the campus consumes data at an average of more than 7 Gbps over a five-minute interval.

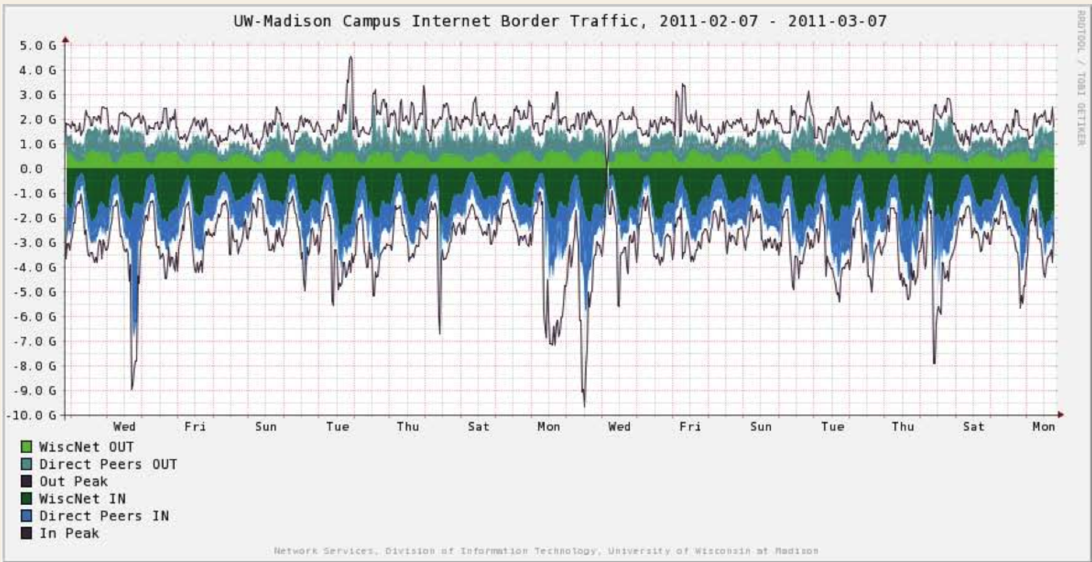

Figure A. A month of UW-Madison Internet border traffic.

Moving forward we will continue to apply and leverage the knowledge and tools we developed in building and operating a shared campus-wide HTC infrastructure to other CI activities. This includes community-wide open source software efforts like the Laboratory for Optical and Computational Instrumentation (LOCI). We will continue to expand our networking capabilities through the BOREAS partnership and the Northern Tier Network Consortium (NTNC).

- The new NSF data management policy requirements [128] create an additional incentive for a coordinated campus cyberinfrastructure.
- Faculty who coordinate with campus leadership pre-award may in some circumstances be able to take better advantage of existing campus CI and expedited integration of the new CI their award brings, bringing both financial and time efficiencies and improving competitiveness for grant funding.

Economic times are straining IT budgets along with all others at all levels of organization from the individual campus to the federal budget. Any economies of scale or more cost-effective expansion of capabilities that can be achieved by making better use of existing funding sources will be of particular value in such times. In some cases consolidation of systems may be valuable, in other cases better interoperability of distributed facilities may improve overall effectiveness of campus cyberinfrastructure.

There exist a number of excellent examples of campus cyberinfrastructure plans [129-132]. Successful and successfully implemented CI plans seem to have the following features largely in common:

- They are developed through collaboration between campus intellectual leadership, infrastructure providers, and faculty to achieve maximum buy-in and address as broad a set of requirements as possible.
- CIOs are regarded as part of the campus intellectual leadership, and are deeply engaged in the development of a campus CI plan and deeply involved in its subsequent implementation.
- Senior campus leadership is involved and committed to the CI plan's success.
- They place value on the research and professional staff who deploy, operate, and support CI.
- They include a focus on delivery of services to researchers and other users, an expected impact of the services, and a plan for assessing impact.
- They utilize economies of scale to deliver value and include analysis of sustainability.
- They distinguish and separate funding for research CI as opposed to other IT infrastructure.

While these general features seem common to notable examples of successful CI plans across many institutions, there is no single blueprint for a particular architecture or a particular approach to cyberinfrastructure governance [133] that determines success. In general, any plan seems better than no plan, and a good plan seems essential to optimal use of any campus's cyberinfrastructure. This leads to a strategic recommendation aimed at the leadership of universities and colleges:

Strategic Recommendation to university leaders and the US higher education community #2: Every institution of higher education should have a strategic plan, developed and endorsed at the highest level of its governance, for the establishment of a coherent cyberinfrastructure. Such a plan should have as one of its features a strategy for maximizing effective utilization of the institution's aggregate research cyberinfrastructure and minimizing impact on the global environment. Such a plan should also include ongoing funding for staff to support implementation and use of cyberinfrastructure hardware and software.

In creating such plans, the higher education community can address the bridging challenges of interoperability and sharing of similar facilities within a single administrative point of control, as well as peering between like CI facilities over multiple administrative points of control or between different and varied CI facilities and multiple points of control. Several well-known national and international cyberinfrastructure projects began at the campus level. The Condor project [125] used the University of Wisconsin campus as its initial proving ground. The ROCKS cluster management software [134] was first developed and gained popularity within the University of California – San Diego (UCSD) campus. Continued innovation at the national level must depend on new discoveries in development of CI software. Diversity in approaches to CI software at the campus level, at campuses where researchers are making new discoveries and developments in this area, is important to the long-term best interests of the US science and engineering community that campuses can remain testbeds for innovation in cyberinfrastructure.

Strategic plans for cyberinfrastructure should explicitly address staffing and the human element of cyberinfrastructure. Expert one-on-one consulting is a well established model for supporting researchers using advanced cyberinfrastructure, and this remains an essential element of research at the cutting edge. There are, however, other models for support that leverage online tools and community support and which can be well implemented even at small institutions [135, 136]. The capabilities of a campus cyberinfrastructure to support research and innovation depend principally on what hardware and software resources are available locally, and how effectively these resources are used. Investing in hardware without support personnel may mean that the hardware is ineffectively used; investing in hardware, software, and personnel is essential if campus cyberinfrastructure is to be effective in advancing research.

All campus CI plans should include explicit plans regarding what we have identified (by analogy with networking terminology) as the peering aspect of campus bridging: peering from the campus to state, regional, national, and international CI facilities. So doing will facilitate the use of state and federally funded cyberinfrastructure beyond the boundaries of a particular campus. A strong focus on this aspect of planning may be particularly valuable for institutions with limited local cyberinfrastructure hardware facilities, and in this case investment in support personnel may be particularly beneficial.

This strategic recommendation, if carried out effectively, can aid research universities in addressing global impacts and cost structures. "Greenness" can be thought of as including several components, including: To what extent does an activity contribute to the production of greenhouse gases? And to what extent is the net result of an activity beneficial or harmful to the global environment?

An effective strategic plan that extracts the greatest possible utility out of computing hardware over its life span should minimize the unnecessary production of greenhouse gases, since such plans would minimize energy used by systems that are idle. An interesting example of energy minimization uses BIOS changes to put systems in to deep sleep mode automatically when not in use [137]. This reduces electrical consumption. However, the building of any computer involves the use of a significant amount of raw materials and energy. As discussed earlier there is more demand for cyberinfrastructure resources than there are resources. Given this, the 'most green' approach to use of computational resources may be to maximize its energy consumption through keeping it operating at maximum possible usage levels – at least as long as the research and education activities being carried out are meritorious. This gets to the second aspect of greenness: to what extent is the net result of an activity beneficial or harmful to the global environment? There are two ways then that recommendations made in this report should maximize the net benefit of campus cyberinfrastructure in terms of global benefits. Improvements suggested in this report should decrease barriers to full use of campus cyberinfrastructure, thus enabling maximal utility of cyberinfrastructure hardware over the course of its useful life, and supporting breakthrough and practical research enabling the development of human societies in ways that are in harmony with a healthy global environment.

This strategic recommendation is consistent with several recommendations made by the AAU [45], particularly a recommendation that research universities address costs. It seems intuitively obvious that strategic planning should result in improved services and improved effectiveness of investments. Several examples demonstrating this as regards campus cyberinfrastructure exist [138-141], including examples focused on green computing.

2.7. The opportunity for NSF leadership

The national situation of our cyberinfrastructure system is challenging. The United States does not have enough cyberinfrastructure to support current demand by the open science and engineering research community. There are well-founded concerns and considerable debate around problems of tremendous potential global impact, such as global climate change, that desperately call for increased cyberinfrastructure. Our current CI, however, is deployed in islands interconnected with bridges of software that are difficult to find, in disrepair, inadequate, or missing altogether. Fortunately, unlike the problem of the bridges of Königsberg, the problem is not insolvable.

The Königsberg Bridge Problem

The problem of the bridges of Königsberg, depicted in the cover image, asks if the city's seven bridges can be traversed exactly once in a single trip, resulting in the traveler ending back at his or her starting point. In 1736, mathematician Leonhard Euler proved that no solution to this problem existed or could exist.

The National Science Foundation has tremendous opportunity to encourage and align financial resources far beyond its own budget through a combination of technical leadership and prudent financial investment. The Internet we enjoy today – research networks as well as commodity networks that have revolutionized business and communications – are the direct result of NSF leadership in networking in the 1980s. The NSF then exerted a tremendous unifying force in networking standards by prudently selecting TCP/IP as the single networking protocol for NSFNET [142]. This decision aligned and organized millions of dollars in research and development investment by public and private sectors, leading to the Internet revolution and the billions of dollars of revenue created in the process. There isn't an exact analogy between networking protocols and the challenges of creating an effective national cyberinfrastructure through campus bridging, but the NSF has a tremendous opportunity to influence and direct with strategic investments from its own budget a total investment by public and private sectors much greater than the actual budgets under control of the NSF.

In the remainder of this document, we make a series of recommendations to the NSF regarding the core area of concern of the Task Force on Campus Bridging and make recommendations that are jointly to the NSF and to other entities regarding this same area. We emphasize the importance of and make comments on recommendations made by other ACCI task forces that overlap in significant ways with matters related to the general area of campus bridging. Since the challenges facing the overall cyberinfrastructure ecosystem involve many stakeholders, recommendations to campus leaders are in some cases made within the text of this document.

Planning A Strategy for Research Cyberinfrastructure

"A Research Cyberinfrastructure Strategy for the CIC" provides a CIO perspective on how to respond to disciplinary imperatives behind investment in cyberinfrastructure for research and education. This document describes good practices, culled from the collective wisdom of the COIs of the Committee on Institutional Cooperation (http://www.cic.net - the twelve universities of the Big 10 plus the University of Chicago. These good practices, that support greater coordination at every level, include:

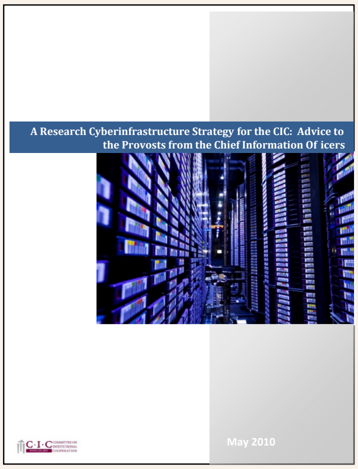

Figure B. Cover of A Research Cyberinfrastructure Strategy for the CIC.

- Plan.
- Share (at the highest level possible).
- Design funding models that promote scholarship and stewardship.
- Rely on user governance.
- Conduct cyberinfrastructure impact analysis.

This strategy document recommends investment in:

- Preparing for "federated identity management" and other enabling technologies for virtual organizations.
- Maintaining state-of-the-art communication networks.
- Providing institutional stewardship of research data.
- Consolidating computing resources while maintaining diverse architectures.
- Expanding cyberinfrastructure support to all disciplines.
- Exploring cloud computing to manage long-term financial commitments.

Anyone interested in cyberinfrastructure planning, particularly CIOs, can find valuable information in this document at http://www.cic.net/CyberInfrastructurePaper.

3. Identity management and authentication

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Effective, efficient federated identity management and authentication are among the most basic requirements for effective use of distributed cyberinfrastructure. For CI providers, this is key to identifying researchers trying to use their services. For CI users and collaborations of CI users, this is key to accessing a variety of campus and remote CI resources and also to managing access to information among collaborations of researchers from different institutions.

For all these reasons, identity management, namespace management, and authentication remain critical and ongoing challenges in coordination of cyberinfrastructure from the campus level to the national levels. Identity management is one of the critical obstacles to effective campus bridging and more effective use of the nation's human resources and CI assets. There have been demonstrated successes in delivering CI resources by making use of authentication via the InCommon Federation [143] through use of the SAML protocol. These successes include most notably the TeraGrid [23] and, at smaller scales, the National Institutes of Health (NIH)-funded Indiana Clinical and Translational Studies Institute [144], and the Committee on Institutional Cooperation (CIC) [145] Chief Information Officer (CIO) group.

The Task Force on Campus Bridging reaffirms and expands upon a recommendation made in the EDUCAUSE / Coalition for Academic Scientific Computation joint report "Developing a Coherent Cyberinfrastructure from Local Campus to National Facilities: Challenges and Strategies" [12], specifically:

> ***Strategic Recommendation to the NSF #1: As part of a strategy of coherence between the NSF and campus cyberinfrastructure and reducing reimplementation of multiple authentication systems, the NSF should encourage the use of the InCommon Federation global federated system by using it in the services it deploys and supports, unless there are specific technical or risk management barriers.***

Use of the InCommon Federation system requires a specific set of guidelines and quality assurance processes for every campus that becomes a member of InCommon. InCommon-based authentication is used in delivery of a service across domain boundaries, where a person with an identity in one name management / authentication domain accesses a service beyond that domain (generally in inter-institution or inter-campus situations). To aid campuses and projects in the effective deployment of a common identity management system through the use of InCommon, the NSF has funded the creation of an "InCommon Roadmap for NSF Cyberinfrastructure" [29, 30]. The Roadmap document offers guidance for campuses and CI projects to implement a minimal level of participation in InCommon in order to support NSF researchers. The improving ability of Microsoft Active Directory Service (ADS) to support InCommon credentials makes use of such credentials much more accessible for small institutions. For institutions with very low numbers of potential users of NSF facilities, and limited ability to implement namespace management systems, it is now possible to purchase InCommon credentials for individual researchers or students through private companies (such as ProtectNetwork [146]), making this approach feasible for all institutions of higher education.

The NSF has also funded the CILogon Service [148], which provides a bridge and translation service between InCommon and the International Grid Trust Federation-based (IGTF) [149] public key infrastructure certificates [150] (a.k.a. "grid certificates") that are now common for NSF cyberinfrastructure facilities.

The NIH has already announced, and partially implemented, plans to deploy a series of applications accessible only through use of InCommon-based authentication [143].

An NSF requirement to employ the InCommon Federation global federated system for identity management for all systems and services it funds – including its use for access to MRI-funded facilities when used by individuals accessing such facilities from the namespace in which said instrument resides – combined with NIH adoption of InCommon should lead the nation to consistent use of a single, interoperable, federated identity system. To the extent that this will lead to many more institutions joining the InCommon Federation, and thus improving and documenting their own identity management processes, implementation of this strategic recommendation on the part of the NSF will lead to improved cybersecurity among NSF CI facilities and services and US higher education generally.

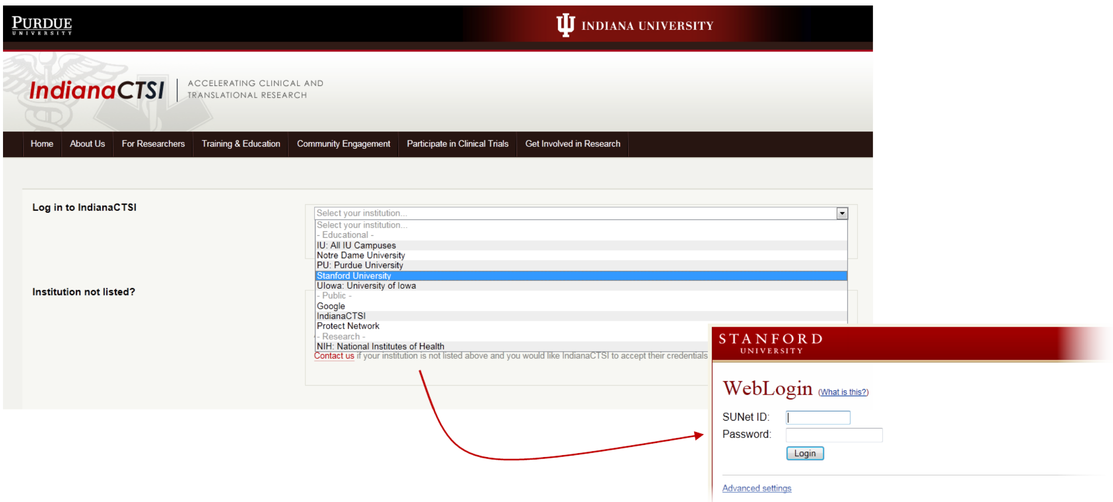

Figure 18. Use of software tools such as GridShib, the SAML protocol, and InCommon standards compliance for authentication allows a researcher to access web-based tools, as shown here, and authenticate via the authentication system at their own home institution (in the example shown here, Stanford University). NIH has developed a roadmap for use of InCommon as the basis for authentication for many of its institutional applications [147]. (Image provided by Alan Walsh, licensed under the Creative Commons 3.0 unported attribution license [20].)

4. Fostering a mature cyberinfrastructure

4.1. NSF leadership in fostering a mature cyberinfrastructure

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A recent paper [13] noted that the word cyberinfrastructure as used by the National Science Foundation typically indicates cutting-edge facilities where the importance of new capabilities is viewed as a reasonable tradeoff for a certain degree of unreliability. Certainly we tolerate as a community a degree of uncertainty in the reliability of cyberinfrastructure that we would not happily tolerate in the plumbing of our homes. If cyberinfrastructure is to be a widely used and effective tool, and if the word cyberinfrastructure is ever to enjoy wide adoption, then the NSF must place some significant effort and funding into fostering a more mature, more simple to use, better supported, well-coordinated, and effective national cyberinfrastructure. Based on the discussion above, particularly the example of NSF leadership in the creation of NSFNET, the Task Force on Campus Bridging makes the following strategic recommendation, which is expanded upon and explained in more detail below:

> ***Strategic Recommendation to the NSF #2: The NSF must lead the community in establishing a blueprint for a National Cyberinfrastructure. Components of this leadership should include the following strategic approaches to funding cyberinfrastructure:***
>
> - ***When funding cyberinfrastructure projects that are intended to function as infrastructure the NSF should use the review criteria and approaches that are generally used for research infrastructure rather than the criteria used for scientific discovery awards. Such awards should be made in ways that complement existing infrastructure and align with best practices, appropriate international standards, and the NSF vision and plans for CIF21.***
> - ***The NSF should establish a national cyberinfrastructure software roadmap. Through the Software Infrastructure for Sustained Innovation (SI^2) or other programs, the NSF should seek to systematically fund the creation and ongoing development and support of a suite of critical cyberinfrastructure software that identifies and establishes this roadmap, including cyberinfrastructure software for authentication and access control; computing cluster management; data movement; data sharing; data, metadata, and provenance management; distributed computation / cycle scavenging; parallel computing libraries; network performance analysis / debugging; VO collaboration; and scientific visualization. Funding for personnel should be a strong portion of such a strategy.***

- ***The NSF should continue invest in campus cyberinfrastructure through programs such as the Major Research Infrastructure (MRI) program, and do so in ways that achieve goals set in the Cyberinfrastructure Vision for 21st Century Discovery and a national cyberinfrastructure software roadmap.***

This recommendation follows directly from discussion in this report, discussions at all three workshops held by the Task Force on Campus Bridging, and two prior workshops on the topics of cyberinfrastructure and software [12, 151]. This recommendation in its specific form is completely consistent with two recommendations made by the AAU – that the federal government should "fund research sufficiently and predictably" and "increase support for facilities and equipment" [45].

This strategic recommendation enumerates several types of software that might be supported. The Campus Bridging: Software & Software Service Issues Workshop Report [40] identifies a general area of challenge with software services: the difficulty of identifying resources and finding data (or even finding directories of data). Rather than identify this as a category of software that is needed, the Task Force on Campus Bridging identifies this sort of capability for resource discovery as functionality that is generally needed in any of sort of cyberinfrastructure software including those listed above. Further expansion on needs for particular types of cyberinfrastructure software is provided in Section 9 of this document, which highlights recommendations made in reports by other ACCI Task Forces, and in those task force reports themselves [7-11]. Collaboration, data management, visualization, and high performance libraries are among the specific types of software dealt with in considerable detail in these reports.

None of the ACCI Task Force reports deal extensively with the topic of cybersecurity. This topic is addressed in other reports, including the President's Council of Advisors on Science and Technology (PCAST) report titled "Designing a Digital Future: Federally Funded Research and Development Networking and Information Technology" [6], "Leadership Under Challenge: Information Technology R&D in a Competitive World" [3], and the reports of the NSF Cybersecurity Summits [152-154]. However, campus bridging and cyberinfrastructure for science and engineering have some specialized cybersecurity challenges related to collaboration, and hence present an ongoing need for additional cybersecurity research and development. Indeed, some of the challenges to effective campus bridging are side effects of cybersecurity measures taken to prudently secure cyberinfrastructure facilities. Technology and software for cybersecurity and campus bridging will need to evolve together, over time, to meet effectively the goals of both effective security and campus bridging.

The observation that cyberinfrastructure is infrastructure seems almost tautological. However, it has been in practice the case that CI proposals are sometimes evaluated using the NSF criteria appropriate to discovery awards. In review of grant proposals submitted to the NSF, it is appropriate to evaluate the creation of cyberinfrastructure as a discovery process on the basis of the intellectual merit or the transformative nature of the computational and data-intensive science and engineering that contribute to the design and execution of new cyberinfrastructure. This represents the "discovery" strategic goal depicted in the NSF 2006-2011 strategic plan [15] and included as Figure 1 in this report. However, when a proposal aims to implement cyberinfrastructure as research infrastructure (in the 'infrastructure' sense of NSF strategic goals), it should be evaluated on the basis of the merit of the activities it enables and the functionality of the cyberinfrastructure as infrastructure in service of science and engineering. These factors may in such circumstances be more important than the novelty of the underlying cyberinfrastructure itself. In particular, for facilities and services it ought generally be most important for CI to function reliably, predictably, and consistently, and in so doing enable transformative research. It may be impractical – and likely unrealistic – to ask that a facility enable transformative research, be sufficiently reliable that domain scientists will be willing to depend on it, and simultaneously be so novel that the creation of such facilities would be regarded as transformative as a computer or computational science research discovery project. (This tension between creation of CI that is transformative in terms of computer science and CI that enables reliable use by scientists is noted in Stewart et al. [13]). The first bullet point in the strategic recommendation above is a generalization and significant extension of a recommendation in the report "Cyberinfrastructure Software Sustainability and Reusability: Report from an NSF-funded workshop" [151].

The NSF can provide significant aid in standardization and achievement of economies of scale by creating a national CI software roadmap. In so doing the NSF can support the development of robust cyberinfrastructure software, provide guidance via decisions made in funding large software projects, such as software institutes to be established via the Software Infrastructure for Sustained Innovation program (SI^2) [35].

As mentioned earlier, NSF leadership, by insisting on a layered TCP/IP architecture at the outset of the NSFNET program, was crucial to NSFNET's success. This combination of leadership with major funding of the backbone and partial funding of the regional networks led to enormous collateral investments by campuses, who provided full funding for campus networks, and eventually by industry to create the Internet we know today. As with networking, the challenge in defining and deploying a national cyberinfrastructure cannot be met with NSF funding alone, and any approach must take the CI of other agencies and nations into account. Cyberinfrastructure's complex and distributed nature, the variety of challenges facing researchers in different disciplines, and the yet nascent state of much CI software mean that it will be harder to have standards that propagate naturally in the same way that standardization on TCP/IP did. Still, the NSF is making critical investments in national cyberinfrastructure through Track I and Track II awards and more major investments are anticipated through TeraGrid XD and other programs [155]. This investment, combined with prudent yet clear guidance from the NSF, will allow stakeholders at the campus, regional, and backbone layers to "think globally and act locally," much as was the case with NSFNET. NSF leadership is more difficult in regards to campus bridging due to the complexity and variety of software involved, but just as critical as funding, if not more so.

The goal of the SI^2 program is to fund CI software development, hardening, support, and sustainability for important and widely used software. The Task Force on Campus Bridging recommends that this program be used as a basis for developing a roadmap for a national cyberinfrastructure. One of the challenges facing the NSF-funded CI community right now is that there are a large number of modestly sized projects producing CI software that are in many cases of excellent quality. It seems beyond the scope of this committee's charter, and to be potentially disruptive as well, to make a recommendation regarding a selection, e.g., of one of the several excellent cluster management tool suites. Even if the committee were to manage to make correct decisions, it would be counterproductive to identify recommended standard tools without having such recommendations associated with increased funding for the support burden that would surely follow if the national research community heeded such recommendations. Rather, we recommend a specific process based on strategic use of the SI^2 program that should enable the natural development of a roadmap and funding for software development and support, and do so via well-established NSF peer review processes.

Establishing this roadmap for some cyberinfrastructure software via NSF peer review of proposals creates a right and proper way for making decisions that are critical to the US research enterprise. This process will also lead to the best possible chances for widespread community acceptance of outcomes. Earlier in this document we made the case that on campuses where researchers were engaged in the creation of new cyberinfrastructure software, the opportunity to experiment at the campus level was important in continued innovation relevant to the nation as a whole. Without contradicting that statement we make two additional observations. First, very few researchers are in a position to create an entire new framework for cyberinfrastructure from scratch. Most researchers focus on one or a few of the many different areas of cyberinfrastructure software in use today. In that sense, having a clearly defined national blueprint for cyberinfrastructure makes this sort of innovation simpler, since such a framework would more clearly define the matrix within which innovation on particular elements of cyberinfrastructure would be invented or advanced. Furthermore, there are many university and college campuses in the US where there are few or no scientists engaged in the creation of cyberinfrastructure software. For such campuses, a clear roadmap of well-defined, mature, well-supported software would be extremely beneficial. At present there are for many types of cyberinfrastructure a variety of very similar tools available, all with slight differences in functionality and few provided with robust support for the national research and research education community. In this environment, natural human reactions include expressions of "not invented here" syndrome and a tendency to pick a tool that someone in a lab or department understands well. A clear national cyberinfrastructure roadmap – the identified tools well supported at the national level – would make it easier for the higher education community generally to achieve economies of scale that are now seeming difficult to obtain.

Better software, usable both on campuses and on national resources, would enhance the utility and effective and efficient use of CI at all levels and would address the two aspects of campus bridging described earlier: interoperability and sharing of similar facilities within a single administrative point of control, peering between like CI facilities over multiple administrative points of control; or between different and varied CI facilities and multiple points of control.

At present there exist major awards in the area of authentication and access control, parallel computing libraries, VO collaboration, and scientific visualization [148, 156-158]. This suggests that immediate priority should be placed on the areas of computing cluster management; data movement; data, metadata, and provenance management; distributed computation / cycle scavenging; and network performance analysis / debugging.

The SI^2 program seems to fulfill recommendations made in a prior NSF workshop [151] that "NSF should be prepared to make decisions to fund a succession of software, over time, that provide key required capabilities and in so doing focus on a limited number of robust codes maintaining a particular functionality at any given time" as well as similar discussions that have been in discussion and in draft form within the ACCI Task Force on Data and Visualization for some time. Through choices made in funding a set of such Scientific Software Innovation Institutes, the NSF will and should establish a de facto roadmap for a national cyberinfrastructure that spans major national centers and campus cyberinfrastructures.

Once a CI roadmap is established, the NSF must continually reinforce it through its own funding decisions. NSF programs such as Major Research Infrastructure (MRI) have at times as a side effect of funding implicitly rewarded lack of centralization and interoperability in campus cyberinfrastructure. The NSF should be more general in how it defines a cyberinfrastructure instrument – allowing the option that an instrument funded through the MRI program may be a component of a larger campus, regional, or national cyberinfrastructure. MRI evaluation criteria should also explicitly include preference for use of open source cyberinfrastructure software, particularly that which is supported by Scientific Software Innovation Institutes or other standard setting and software producing organizations. In order to support effective bridging of NSF-funded facilities, MRI budget guidelines should include and encourage budgeting of the network costs needed to appropriately connect MRI-funded CI facilities and integrate them effectively within campus and national cyberinfrastructure. Efficient use of natural resources and minimization of impact on the global environment should be explicitly considered as review criteria, leading naturally to better coordination of infrastructure at campus, state, regional, and national levels.

The current tiered scope and budget structure now included in the MRI solicitation creates a natural opportunity for 'regional' activities that might be coordinated through organizations such as SURA, CIC, Great Plains Network, and Regional Optical Network operators. To encourage focus on the MRI program as a way to foster a coordinated and interoperable national cyberinfrastructure, the NSF should consider adopting a minimum target for funding of cyberinfrastructure activities via the MRI program.

The creation of such a national blueprint for a national cyberinfrastructure should be particularly helpful for smaller universities and colleges and for minority-serving institutions (MSIs). MSIs and other smaller schools often have excellent faculty and staff constrained in number and activities by budgetary pressures. It is often impossible for individuals at such institutions to get federal funding to create their own middleware. It is often beyond the available faculty and staff time to take 'almost robust' middleware as it exists now and implement it in ways that seem usable and useful to researchers, educators, and students at such institutions. A national CI blueprint accompanied by more robust and easier to install software would decrease dramatically the barriers experienced by those at MSIs and smaller colleges and universities generally.

4.2. Commercial cloud services (Infrastructure as a Service and related technologies) as part of a mature national cyberinfrastructure

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As discussed earlier, commercial service providers are becoming increasingly critical parts of the scientific workflow process. This includes "cloud" providers of compute and storage services, as well as service providers such as Google Docs, Dropbox, etc. Their integration into the scientific CI is not without hurdles. While some of these hurdles are technical, we focus here on the legal and financial hurdles, which are as challenging if not more so.

The use of commercial services with various scientific and academic data leads to policy and privacy concerns, including US laws and policies (e.g., Family Educational Rights and Privacy Act, Health Insurance Portability and Accountability Act) and uncertainty about compliance with export laws when applicable, since there are often no "digital borders" restricting services to the US or any particular nation. In terms of practical considerations, the cost of data movement between the commercial CI space and the researcher's or other CI is often prohibitive at the scale of scientific data.

Strategic Recommendation to commercial cloud/IaaS providers #1: Commercial Cloud/IaaS providers must work with the US open research community, particularly the community of NSF-funded researchers, to reduce barriers to use of such facilities by the US open research community. Such barriers include technical issues such as the quality of connectivity between the research and education and commercial sectors, business model issues such as transport costs, and policy issues such as the control of geographic location of data for privacy, national security or intellectual property reasons.

We note with considerable gratitude to commercial cloud providers that our recommendations to them have decreased in number since this report was initially drafted. Either of their own volition, or aided by discussions at Task Force on Campus Bridging workshops, commercial cloud providers have changed the intellectual property terms associated with use of their services in ways that have removed obstacles to academic use of such facilities. In either case, the Task Force on Campus Bridging appreciates these changes being made by commercial cloud providers and takes this as a sign that other barriers to use can be addressed successfully in the future.

5. Data movement and networking

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Campus bridging supports access by researchers (and geographically distributed collaborations of researchers) to local and remote resources (including instruments, storage, computing resources, and visualization facilities). The role of data and networking in campus bridging is thus in continuity with the close explicit teaming in the late 1980s of the NSFNET program with the NSF Supercomputer Center program. Whether explicit or implicit, this teaming has continued in practice. What is new, however, is that recent advances in such science fields as genomics and bioinformatics are seeing data generation surge in its quantity, availability, and centrality to science. Fortunately, as this "data deluge" has progressed, advances have allowed cost-effective data storage. Unfortunately, the same cannot be said for our abilities to curate, move, and remotely share these data. The report of the first workshop (on data and networking) held by the Task Force on Campus Bridging [39] and the ACCI Task Force on Data and Visualization Final Report [8] detail many aspects of this phenomenon, its capabilities, the opportunities created. A critical finding is as follows:

> **Finding 6. Data volumes produced by most new research instrumentation, including that installed at the campus lab level, cannot be supported by most current campus, regional, and national networking facilities. There is a critical need to restructure and upgrade local campus networks to meet these demands.**

In terms of moving the data, the problem spans from within campuses and extends at every level of networking to national and international networks. The network that researchers need to keep up with data generation has different properties from the regular Internet, including: supporting multiple Gigabits per second (Gbps) both within the campus and across the nation, supporting the flow of large data objects, and supporting visualization. In the 1990s' High Performance Connections program, there was initial emphasis on "meritorious applications," but this was later dropped. This allowed the whole campus to benefit from the program, but had the downside that campus network design became disconnected from the needs of the driving meritorious applications. Furthermore, the data production capability of new instruments, such as next-generation gene sequencers, means that campus networking needs related to research may no longer be met by over-provisioning the entire campus network (as was possible until about ten years ago). Instead, CIOs and campus leadership should adopt new, targeted strategies for meeting intra-campus CI needs that focus on targeted solutions for networking from labs and buildings with high data I/O and networking needs and the main campus connecting points to high-speed research networks.

There are two aspects of data movement and networking that are particularly important to the charge of the Task Force on Campus Bridging:

- For effective bridging in the sense of an individual researcher to a state, regional, or national CI facility it is essential that there be adequate end-to-end network performance.
- New data creation capabilities drive tremendous new demand for high bandwidth network connections between campuses to support campus bridging in the peering sense described in the Introduction – between like CI facilities over multiple administrative points of control or between different and varied CI facilities and multiple points of control.

End-to-end performance has been understood to be primarily a last-mile problem at least since 2000. Even if optimal tuning of all networks were a given, however, many researchers could not effectively move data on and off campuses in order to manage and understand them because the campuses have inadequate connections to high-speed research networks. Part of this problem resides with university and college campus leadership, CIOs, and state funding levels. Every campus of a higher education research institution should have a connection to research networks to support research and research education that are at least 1 Gbps now, and 10 Gbps by 2020 as a component of its basic infrastructure. This baseline will not, however, meet current, high priority data movement needs.

It is extremely important overall that the NSF focus attention on and, where appropriate, fund the scaling up of end-to-end data movement capabilities that match the growth in data that are important and of long term value. New capabilities in dynamic allocation of bandwidth offered by Internet2 and National Lambda Rail offer the possibility of highly cost effective transfer of data within and between those networks via 10 Gbps dynamically allocated lambdas. However, it can be extremely expensive to fund a 10 Gbps connection from campus to one of these national backbone providers. The Task Force on Campus Bridging thus makes the following strategic recommendation:

> ***Strategic Recommendation to the NSF #3: The NSF should create a new program funding high-speed (currently 10 Gbps) connections from campuses to the nearest landing point for a national network backbone. The design of these connections must include support for dynamic network provisioning services and must be engineered to support rapid movement of large scientific data sets.***

As with other earlier recommendations, this recommendation is consistent with the AAU that the federal government should "increase support for facilities and equipment" [45]. Such a program could be effectively and productively modeled on the NSF High Performance Network Connections program [159], as that program did initially focus on meritorious research applications. In order for such a program to be effective, NSF funding must be one part of an overall solution that provides high-quality, high-bandwidth end-to-end performance from the labs involved in highly meritorious research to national backbones and beyond. A review criterion for such proposals should thus be the extent to which the local campus provides proper 'last mile' connectivity to key research labs on campus. In the future, as network technology advances, 10 Gbps connections may become routine, and by that time data needs may have grown to a point that the NSF should initiate a program encouraging 40 Gbps or 100 Gbps connections.

Data collected at universities (with and without NSF funding) are a national asset and are critical to reproducible modern science and to the data deluge. We are in danger of having vast amounts of science that cannot be reproduced easily or at all, and as discussed in the ACCI Task Force on Grand Challenges Final Report [7] researchers are now producing precious and costly data without the means to store those data locally or to move them to a regional or national repository. New NSF grant proposal guidance calling for the creation of data management plans [160] will increase demand for local and national data archival facilities. Efforts such as DigCCurr [161] CIRSS [162], and HathiTrust [163] show examples of innovative approaches to the challenges of data management, curation, and access. Effective data management, curation, and access have benefits beyond research. Making data widely available is highly beneficial to the process of education and the generation of an excellent 21st century workforce.

The Task Force on Campus Bridging especially and particularly endorses recommendations made by the ACCI Task Force on Data and Visualization that the NSF fund national data repositories [8]. The most important data collected across the nation must be safeguarded securely over the course of decades, and the only practicable way to achieve this seems to be for the NSF to lead with some funding for core long-term data archival facilities and curation services. This is a campus bridging issue, since for "the 4th Paradigm" [47] of data-centric research to become a widespread reality, researchers on campus will have to be able to access data, understand data, at times subset and selectively obtain portions of large remote data sets, and then return the results of their research to some sort of curated archive.

Even if such services are funded, there will remain a tremendous need for facilities that serve the function of moving large amounts of data between campuses and national facilities such as TeraGrid XD, and among all of these facilities and campuses where it can be visualized, analyzed, and used in research education and data repositories for long-term storage. At present there are two candidate technologies for large scale bulk data movement (which are not necessarily mutually exclusive) – globally accessible file systems and data transport services such as Globus Online [164]. Both approaches can achieve highly effective and efficient bulk data transfer. Global file systems have been demonstrated to facilitate collaboration, scientific workflows and metadata/provenance management, and remote visualization. It may be possible that services such as Globus Online may be able to support such activities in the future as well. In any event these types of capabilities are critically important and central to effective campus bridging, which leads to the following strategic recommendation:

Strategic Recommendation to the NSF #4: The NSF should fund national facilities for at least short-term storage and management of data to support collaboration, scientific workflows, and remote visualization; management tools should include support for provenance and metadata. As a complement to these facilities and in coordination with the work in Recommendation #3, the NSF should also fund the development of services for bulk movement of scientific data and for high-speed access to distributed data stores. Additionally, efforts in this area should be closely coordinated with emerging campus-level data management investments.

As with several other recommendations, this recommendation is consistent with, though more specific than, two recommendations made by the AAU – that the federal government should "fund research sufficiently and predictably" and "increase support for facilities and equipment" [45].

Campus Cyberinfrastructure and Bridging at Pennsylvania State University

The Research Computing and Cyberinfrastructure (RCC) group, a unit of Information Technology Services at The Pennsylvania State University, is a central facility that serves an essential role in meeting the high-end computational and CI needs of the university faculty and students. In partnership with the research community, RCC builds and operates cost-effective, high productivity resources for large-scale computation, visualization, virtual reality, and data management. Users are able to exploit capacity gaps created by differences in timing of peak computational workflows submitted by different research groups; thus each group enjoys access to a significantly greater number of cycles than if they operated independent smaller clusters. RCC delivered over 32 million core hours spread across 3.7 million jobs in 2010.

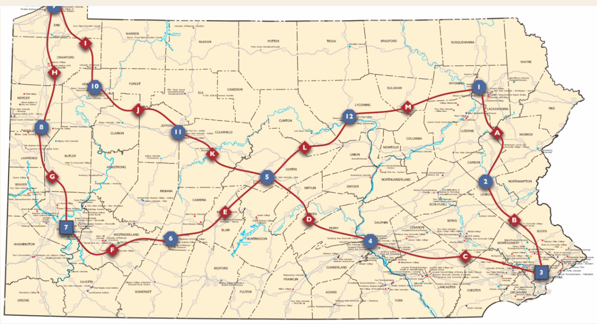

Figure C. The PennREN broadband network will support Penn State's partners across Pennsylvania.

The RCC group operates approximately 6000 cores and 550 terabytes of storage distributed across three different data centers at Penn State's University Park campus. While the capacity of university's standard network backbone doubles every 48 months, research-related data doubles every 12-18 months. In order to address this gap, a dedicated research-only 10 Gb/s Ethernet network connects the three data centers. In order to meet the challenges of data-intensive research, the research-only network will be expanded to directly connect individual collaboratories. The research network will have a direct connection to high-speed national networks such as NLR, Internet2, and DOE ESNet.

RCC facilitates intra- and inter-institutional collaborations by working with national computing centers funded by NSF, DoE, NASA, NIH, and DoD. RCC facilities are well connected to the national research cyberinfrastructure via Internet2 and National LambdaRail (NLR). Penn State is taking an active role in Keystone Initiative for Network Based Education and Research (KINBER), a coalition that is leading the implementation of the Pennsylvania Research and Education Network (PennREN). When completed in 2012, the $129 million PennREN will be a statewide broadband network designed to support educational, research, health, and economic development partners across Pennsylvania (Figure A). PennREN will not only improve inter-campus connectivity among 24 campuses of Penn State, including Hershey Medical Center, but also help each of these campuses better connect with national cyberinfrastructure via networks such as NLR, Internet2, and DOE ESnet.

6. Networking research

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While optical networks offer data movement literally at the speed of light, even this speed induces latency of some import at a national or international level. The speed of light latency is a fixed and unavoidable fact in computer networking. Bandwidth, on the other hand, does continue to grow, though this growth is increasingly taking the form of multiple parallel streams, with the speed of each stream growing more slowly. This combination of increasing bandwidth and fixed speed-of-light delays makes the management of the bulk data flows and remote visualizations needed for campus bridging intrinsically difficult. Furthermore, actual performance of networks is often far below theoretical performance levels sometimes for mundane reasons (such as improper tuning of network parameters) or because of significant challenges in scheduling and managing network resources.

The Global Environment for Network Innovations (GENI) [165] "is a virtual laboratory at the frontiers of network science and engineering for exploring future internets at scale." GENI, which is sponsored by the NSF, is focused very much on large-scale internetworking and global networking. This research is critically important and must continue, and will be of great aid in bridging at scale – large amounts of data across long haul networks within and between nations. GENI embodies an initiative that responds to recommendations regarding network and information technology made in the PCAST report "Leadership Under Challenge: Information Technology R&D in a competitive world" [3] and a variety of federal planning documents, including the 2008 "Federal Plan for Advanced Networking Research and Development" [166]. More recently, there are several recommendations regarding networking contained in the December 2010 PCAST report "Designing a digital future: federally funded research and development in networking and information technology" [6]. Most of these focus on large scale and long-haul networks. The Task Force on Campus Bridging endorses all of those recommendations. The quest for more efficient protocols, and a drive to make 100 Gbps (and more) networking routine is important and must continue with vigor and strong federal funding.

As noted in several of the reports already cited, however, there is much more to networking and networking research than the important process of building bigger, higher capacity networks. First, achieved performance is often far below theoretical capabilities – by an order of magnitude or more – due to tuning and configuration issues. Continued research in network operation and network management tools is essential so that existing technology is used as effectively as possible. Further, when one speaks of network performance, one must really say "network performance for what?" The tuning characteristics that support bulk data movement may often be different than needed, for example, for grid computing, email, Web browsing, etc., so continued research on tools such as Phoebus is essential [167].

Tools that enable the bulk movement of data from lab to national facilities and in between is a clear requirement for campus bridging, as the revolution in data-driven high output instruments (such as gene sequencers) has as noted above greatly redistributed – and more widely dispersed – sources of large-scale data collection.

Furthermore, as noted in the Campus Bridging Technologies Workshop: Networking and Data Centric Issues workshop report [39], wide area file systems are essential to supporting data-centric research. Wide area file systems may serve as an intermediary in distributed scientific workflows [168, 169], as a way to share data from a single source with a VO, and as an intermediate waystation from point of origin to a more permanent archive. At present there exist commercial products such as GPFS (from IBM), and open source products such as Lustre. Lustre's status has changed, as Oracle Inc. purchased Sun Microsystems, which had provided support for Lustre. As of the writing of this report Oracle will provide support only for Lustre on hardware purchased from Oracle, but other private entities and consortia have already established plans and services to maintain a version of Lustre as a well supported, truly open, software project [170, 171].

Recent PCAST reports [3, 6] and NSF reports discuss cyberphysical systems [172, 173] and sensor nets [174] – which are as regards networking much more closely linked than may appear at first blush. Both involve potentially highly dispersed sources of data, connected to national research backbones via networks that are perhaps of low bandwidth and wireless. Additional research and development related to sensor nets and cyberphysical systems is essential for campus bridging for two reasons. First, going back to the definition of campus bridging that begins this report, interacting with and understanding data from sensor nets or cyberphysical systems from an individual research lab on campus clearly falls within the general area of campus bridging. Furthermore, as the ability to generate digital data on campus continues to accelerate, campuses themselves become a sort of multidisciplinary sensor net and source of data useful beyond the campus in both science and engineering research, and increasingly in civil safety and protection.

International networking cannot be ignored. The NSF funds international networking infrastructure activities through the International Research Network Connections (IRNC) program, administered by the NSF Office of Cyberinfrastructure. This program funds both circuit infrastructure and supporting services and is the only NSF program to fund international or domestic network connectivity [175]. The current IRNC program funds network global network connectivity to Europe, Asia, Latin and South America and Australia. The NSF funding is supplemented by non-US funding, usually in the form of "balancing connections" from our international partners. In this way, the NSF investment is leveraged to provide significantly more connectivity.   The IRNC infrastructure supports numerous research and education partnerships, ranging from providing network connectivity to enable Pakistan physicists to participate in Large Hadron Collider (LHC) activities and analysis via a partnership with the European Commission, to providing infrastructure to facilitate US universities' "remote campus activities" in China. The NSF lists some projects enabled by IRNC connections [176].

The IRNC infrastructure also facilitates access to global science "instruments," the most well-known of these being the LHC located at CERN in Switzerland. The IRNC links provide access among LHC sites in addition to the LHC optical private network, custom built for the LHC activity. Other "instruments" supported by the IRNC include the e-VLBI astronomy effort and broader cyberinfrastructure activities such as the PRAGMA-GRID project [177].

This modest investment in international connectivity ($40,000,000 spread over 5 years) is significantly leveraged by partnership contributions and provides critical infrastructure support for US global science activities and access to remote resources. Given the expected rise in international data-intensive collaborations and the increased intensity of US global research and education activities, we urge that this project be continued and expanded if possible.

This leads to the following strategic recommendation to the NSF:

> ***Strategic Recommendation to the NSF #5: The NSF should continue research, development, and delivery of new networking technologies. Research priorities funded by the NSF should include data intensive networks sensor nets, networking in support of cyberphysical systems, geographically distributed file systems, and technologies to support long distance and international networking.***

A High-Performance Campus-Scale Cyberinfrastructure at UCSD

The University of California, San Diego (UCSD) has created a campus-scale dedicated 10Gbps campus data utility over the last five years. This has been enabled by nearly a decade of NSF investment in the OptIPuter and Quartzite 10G networking research grants and more recent NSF awards of data-intensive supercomputers to the San Diego Supercomputer Center. UCSD uses dedicated optical fibers, or wavelengths on the fibers, to simplify the process of bridging data-intensive campus-resources from data generation or storage devices, internal or external to the campus, into end-users labs with tiled display wall OptIPortals . This has been done in a fashion that is easily duplicated on other campuses.

Figure D. The Quartzite core enables the OptiPuter and other research at UCSD.

Building on this unique optical infrastructure, UCSD undertook a two-year study of how to create an innovative research cyberinfrastructure (RCI) that can service its data-intensive researchers. The resulting report forms a Blueprint for the Digital University, which is now being implemented by the UCSD Cyberinfrastructure Planning and Operations Committee. The switched dedicated optical network allows the RCI to transform the current campus set of isolated clusters into a high-speed connected data-intensive fabric connecting scientific instruments, remote repositories, and supercomputers with end-user labs. This high performance campus cyberinfrastructure includes a:

- Co-location facility – an energy-efficient, centrally managed datacenter space for hosting computer equipment and related components for individuals, labs, departments, organized research units, or other UC campuses, achieving economies of scale through expenditure and operating-cost savings.
- Centralized data storage – the Triton centrally administered disk storage farm for UC San Diego will be housed in the co-location facility and features high performance, high accessibility, high reliability, and scalability. Its low cost per byte will make this an attractive and cost-effective alternative to commercial storage clouds or ad hoc local storage solutions that do not scale and do not provide data replication and backup.
- Data curation – drawing on the combined expertise of the UC San Diego Libraries, San Diego Supercomputer Center (SDSC), and Calit2, data curation activities will encompass software tools and services to store, analyze, preserve, and disseminate research results in digital form to academia and industry.
- Condo clusters – by combining systems into a single, centrally administered cluster, researchers can save money by pooling system administrators and other services.

- Data Analysis Supercomputer – the SDSC Gordon Data supercomputer is architected for massive data computation, including 256 TBytes of Flash memory, and several TBs of RAM
- Research network – an uncongested, leading-edge network that facilitates research collaborations, high-performance data exchanges, access to co-location facilities, remote storage, and real-time communications.

7. Planning for and learning from cyberinfrastructure projects and facilities

Section 7 reuses text published in Dreher et al._[41] and Almes et al. [39]. These two documents are released under Creative Commons 3.0 Unported Attribution license [20]. This section of text in this Task Force report should be considered a work derived from Dreher et al. 2011 and Almes et al. 2011, and anyone citing text from this section of this Task Force Report is requested to cite Dreher et al. 2011 and Almes et al. 2011 as well, in keeping with the license terms for those documents.

As any discipline matures, it needs to develop objective measures of its effort and success (and failures). Cyberinfrastructure faces the challenges both of its success being indirectly measured through the science it enables, and of needing to be innovative at times to meet emergent demands of collaborative science and engineering. Reading annual reports of CI projects brings out a mixture of directly enabled computational science success stories; various numerical metrics of delivered computational, networking, and data services; and innovative CI advances with varying degrees of success. Additionally, as previously discussed, a fair amount of CI is happening in single-investigator and small groups, with no tracking of expended effort or measurement of CI contributions to successes.

A lack of clear metrics for both effort and success make evaluation of CI technologies, projects, and the field as a whole very difficult. This in turn makes crediting its practitioners and funders a challenge, as well as judging what CI is still "under development" and what is production-worthy. While any set of metrics is likely to be imperfect, it would be an improvement over the status quo.

Our ability as a community to learn from our own experiences has also been impaired by the use of an expedient in the execution of surveys of users of major CI facilities. That expedient has been the frequent past execution of satisfaction and needs surveys without institutional review board (IRB) approval, using the rubric that such surveys are for operational use internal to the organization operating these facilities and not intended to be published. Once conducted, the results of such studies have been included in reports to the NSF, which are not generally accessible to the scientific community and thus not generally possible to cite. And because surveys are in fact a form of human subjects research, the execution of these sorts of surveys without IRB approval has made it impossible to publish the results of such surveys in detail. As a result of avoiding the small amount of work to obtain IRB approvals, the US science and engineering community generally has been denied the opportunity to more systematically learn from work funded by the NSF in the past. One notable exception is the set of studies regarding the TeraGrid led by Ann Zimmerman [98, 99, 178-182]. Still, the TeraGrid has been in production since 2004, with many years of annual surveys. We would know much more – publically and openly – about the TeraGrid if the results of all of the TeraGrid surveys were openly published.

In addition to understanding the impact of prior research activities, it is important on an ongoing basis to plan effectively for future cyberinfrastructure projects. Such planning has already been supported in some cases by the NSF, such as activities preparing for cyberinfrastructure within the Ocean Observatory Initiative [183, 184], the iPlant consortium [185, 186], and planning for TeraGrid eXtreme Digital [32, 187]. As noted in the Task Force on Campus Bridging Workshop on Software and Services report [40], it may be difficult for CI providers to find communities of users, either in the form of small organizations or domain science communities. With that as a basic difficulty, it is all the more important to address the need for concerted effort at bilateral understanding – CI providers understanding domain science community needs, and domain science communities understanding the possibilities presented by use of advanced cyberinfrastructure.

These observations lead to the following Strategic Recommendation for the NSF:

> ***Strategic Recommendation to the NSF #6: The NSF should fund activities that support the evolution and maturation of cyberinfrastructure through careful analyses of needs (in advance of creating new cyberinfrastructure facilities) and outcomes (during and after the use of cyberinfrastructure facilities). The NSF should establish and fund processes for collecting disciplinary community requirements and planning long-term cyberinfrastructure software roadmaps to support disciplinary community research objectives. The NSF should likewise fund studies of cyberinfrastructure experiences to identify attributes leading to impact, and recommend a set of metrics for the development, deployment, and operation of cyberinfrastructure, including a set of guidelines for how the community should judge cyberinfrastructure technologies in terms of their technology readiness. All NSF-funded cyberinfrastructure implementations should include analysis of effectiveness including formal user surveys. All studies of cyberinfrastructure needs and outcomes, including ongoing studies of existing cyberinfrastructure facilities, should be published in the open, refereed, scholarly literature.***

We recognize that this recommendation is not consistent with statements made in the NSF MRI FAQ document [188], which allows the possibility that a data management plan (as called for generally in the NSF Grant Proposal Guide [160]) might not be needed. Fulfillment of this recommendation implies that any MRI award related to cyberinfrastructure would generate data, at least in the form of a user survey (approved by the principal investigator's Institutional Review Board, enabling the results to be openly published).

8. Reward and financial structures in academic research and US research competitiveness

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Finding 2 above discussed how current reward structures run counter to the best interests of the US science and engineering research community as a whole. In short, the reward structure as experienced by individual academic researchers does not properly encourage such researchers to act in ways that create the most effective national cyberinfrastructure, or the most effective overall organization of research particularly as regards transformative research and research that can be pursued successfully by large virtual organizations.

It seems reasonable to suggest that institutions of higher education should change their internal reward structures so that individual faculty members are encouraged to participate in virtual organizations and research collaborations in ways that are consistent with the NSF's focus on transformative research and successful solution of grand challenge problems. This is particularly important as regards scientific challenges that have potential societal impact at the national or global level. Still, the institution of tenure is central to the organization of higher education in the US, and should be changed with care. Thus we make a recommendation for NSF-sponsored study of this issue, and then recommendations based on that study:

> ***Tactical recommendation to the NSF #2: The NSF should commission a study of current reward structures and recommendations about the reward structure – particularly as regards promotion and tenure for faculty – that would better align reward structures as perceived by individual faculty members with the type of large, collaborative virtual organizations that the NSF asserts are required for successful approaches to pressing, large-scale scientific problems and transformative research.***

Better alignment of the academic reward structure and the scientific community structure that the NSF asserts is needed for future science and engineering research should have as a natural side effect a better alignment of national CI facilities at all levels in ways that better enable NSF goals as well.

While large-scale changes in academic reward systems should be considered carefully, some institutions of higher education are already engaged in changes to criteria within their tenure systems. Some institutions are already recognizing the value of forms of academic dissemination other than the peer-reviewed technical article, such as production of open source software, creation of online cyberinfrastructure or "service-oriented architecture" facilities, creation of databases, and addition of data to databases. The Task Force on Campus Bridging makes one general strategic recommendation regarding tenure and promotion criteria, that should better align reward structures faced by individual faculty members more closely with pressing US national interests:

Strategic Recommendation to university leaders and the US higher education community #3: Institutions of higher education should adopt criteria for tenure and promotion that reward the range of contributions involved in the production of digital artifacts of scholarship. Such artifacts include widely used data sets, scholarly services delivered online, and software (including robust, widely useable cyberinfrastructure software and other forms of academic contributions). Such an effort must include creation of new ways to provide peer review of these other, newer types of contributions.

With regards to cyberinfrastructure, several metrics by which software contributions may be evaluated were identified in "Cyberinfrastructure Software Sustainability and Reusability: Report from an NSF-funded workshop" [151].

One aspect of the current tenure system is its emphasis on crediting researchers much more for being the lead author on a peer-reviewed paper than any other level of authorship. One way in which publishing practice can be changed to simultaneously maintain this general approach and yet reward collaboration is the relatively new practice of providing multiple primary authors in different categories of authorship on a collaborative paper – such as the core scientific problems, statistical analysis, methods, or cyberinfrastructure or software implementation. This leads to the following tactical recommendation:

Tactical recommendation to university leaders and the US higher education community #1: Institutions of higher education should continue to press publishers to adopt a strategy of enabling multiple 'primary authors' on research papers particularly so that computer, computational, and informatics scholars can contribute to larger collaborative projects while still being rewarded as primary authors.

These recommendations can be expected to be particularly beneficial in support of younger faculty, as these recommendations will support and reward many general trends in activities of today's younger faculty toward digital collaboration and participation in virtual organizations. Such trends are already apparent and can be expected to accelerate as the millennials pursue graduate studies and emerge as junior faculty (cf [189, 190]). These recommendations are thus similar in intent, although different in specifics, than recommendations made by the AAU to increase support for young faculty [45].

Financial structures and processes also affect campus and national cyberinfrastructure. Cyberinfrastructure facilities and personnel clearly may be included in calculation of facilities and administration (F&A) rates, as described within the Office of Management and Budget Circular A-21 [191]). For example, cyberinfrastructure facilities (clusters, storage systems, networking equipment, etc.) are allowable under the category of capital expenditures. Data centers housing cyberinfrastructure facilities would seem to be eligible for inclusion under the category of large research facilities. Personnel who support cyberinfrastructure should similarly be properly included within the category of general administration and general expenses.

To get a sense of whether research cyberinfrastructure was actually included in F&A rate calculation, members of the Coalition for Academic Scientific Computation (CASC) [84] were asked the following question via email in February of 2011:

> *"Are costs for research cyberinfrastructure (other than federally-funded facilities and budgeted match for those facilities) included in your institutions costs that form the basis for negotiating facilities and administration rates associated with grant budgets?*
>
> *___not at all*
>
> *___some costs are included, but well less (less than 80%) of the full costs to the University or College*
>
> *___most (at least 80%) or all of such costs are included"*

CASC had a total of 65 members in good standing as of the time this question was asked. Of them, a total of 34 responded (52%). The responses to this question are presented in Table 1.

Number of respondents	Percent of respondents	Response
13	38.2%	not at all
15	44.1%	some costs are included, but well less (less than 80%) of the full costs to the University or College
6	17.6	most (at least 80%) or all of such costs are included

Table 1. Responses by members of the Coalition for Academic Scientific Computation to a question regarding inclusion of costs for research cyberinfrastructure in their college or university's calculations of F&A rates.

Clearly, many universities and colleges are not including costs of research cyberinfrastructure in calculation of F&A rates, and many institutions that are including these costs are including well less than the full costs experienced by the institution. Anecdotally, several institutions responding to this question indicated that they did not include such costs at all, or included less than 80% of the costs, but were reconsidering this position and considering inclusion of more research infrastructure costs in F&A calculations and negotiations. This should be done with care, but including cyberinfrastructure costs as part of F&A calculations may be useful for universities and colleges not doing so now. The key considerations in this matter are as follows:

- Cyberinfrastructure that generally supports research activities of a university may fairly be included in F&A calculations.
- F&A costs for administration are capped at 26% of direct costs [191], and the effective rate (the rate universities actually collect as opposed to the negotiated rate) tends to be lower than this. Inclusion of costs as part of F&A calculations which are effectively not counted in the calculations because an institution exceeds the cap or the negotiated rate means that such costs would not result in generation of F&A funds. In addition, costs associated with

any 'above cap' facilities or services could then not be included in calculation of matching funds in a federal grant proposal.

- In some cases it is possible to fund some computing as direct costs in grant awards (obtained competitively through grant proposals). In this case, 100% of the cost of equipment may be included as direct costs, and this may for some institutions be a better choice than inclusion of costs in F&A calculations.

We make an additional empirical observation that the internal approach to distribution of F&A monies received by universities and colleges sometimes promotes extremes in distribution of small computing clusters. These can be inefficient in use of energy and personnel, and may exacerbate the challenges of effectively using the nation's aggregate cyberinfrastructure, as noted earlier in section 2.3.

We believe that the systematic inclusion of cyberinfrastructure costs (facilities and personnel) and the use of such funds for cyberinfrastructure may contribute to making campus cyberinfrastructure sustainable as research infrastructure over the long term. We thus make the following recommendation:

> ***Tactical recommendation to university leaders and the US higher education community #2: US colleges and universities should systematically consider inclusion of some costs for research cyberinfrastructure in negotiation of facilities and administration rates. When this is done, the best use of facilities and administration income associated with grant awards to universities will be to use it strategically within the context of a campus cyberinfrastructure plan.***

This recommendation is cast differently than a recommendation made by the American Association of Universities to the National Research Council Committee on Research Universities regarding facilities and administration costs [45]. The AAU recommends that the federal government "reexamine and reform federal F&A (Facilities and Administration) reimbursement policies and practices." The text surrounding this recommendation points out several of the same areas of concern as the recommendation made here by the Task Force on Campus Bridging. For example, the AAU suggests specifically that:

1. *OMB should mandate that agencies adhere to the rules set forth in Circular A-21 and specifically prohibit agencies from paying universities less than their negotiated cost rates;*
2. *Congress should eliminate the statutory restrictions on cost reimbursement for research funded by the U.S. Department of Agriculture and the Department of Defense;*
3. *OMB should lift the 26-percent cap on cost reimbursement to a more appropriate level;*
4. *In accordance with a recent GAO report, OMB should identify ways to ensure that the rate-setting process for reimbursement is applied consistently at all schools, regardless of whether their rates are set by the Department of Defense or the Department of Health and Human Services;*
5. *OMB should reexamine other inequities in current reimbursement policies across institutions, such as the utility cost adjustment[.]*

All of these suggested actions speak in some ways to the same issues identified by the Task Force on Campus Bridging as financial obstacles to better campus cyberinfrastructure and more effective campus bridging in support of a more effective national cyberinfrastructure.

Having mentioned earlier some interpretations of research that suggests 85% of research computing could be done in clouds [110], and having indicated strong exceptions to this view generally, there is a particular point regarding indirect costs (now referred to as facilities and administration costs) in St. Arnaud [110] that bears particular note. It is clear that in general that there is a strong role for cloud computing as a component of research cyberinfrastructure, and that there are in particular opportunities for economies of scale and important energy / carbon efficiencies possible. However, relevant to the discussion of Facilities and Administration costs, the specific recommendation in St. Arnaud 2010 [110] that "cloud services could be included in the indirect costs of research much like energy is today" is fundamentally flawed, because electrical energy and computing power have fundamentally different relationships between supply and demand. While there are some exceptions (including as examples Magnetic Resonance Imagers and particle accelerators) it is not generally the case except in computing that research capabilities are limited by electrical supply (either ability to obtain it physically or pay for it financially). With computing, both issues can be important limiting factors. However, improvement in efficiency of computing (either in floating point operations per dollar or per Kilowatt-hour) may not necessarily decrease demand. Indeed, an economic theory referred to as the Jevons Paradox [192] states that improvements in efficiency can increase – rather than decrease – the rate of consumption of that resource. There is controversy in general within the economic research community about this concept. However, in terms of cyberinfrastructure this observation matches our experience. Given an increase in computational capacity that allows a researcher with a simulation problem that is, say $O(N^2)$ with respect to the number of subcomponents in a simulation to increase the fineness of the simulation subcomponents by a factor of 10 (increasing computational requirements by a factor of 100), the next step is likely to be a desire to increase the fineness of the simulation by a factor of 100 (increasing the computational requirements by a factor of 1,000). And this is in many cases important in terms of the value of the simulations. Turbulence models are one example of this. Similarly, with respect to data, given the ability to handle terabytes easily and petabytes with some effort, researchers naturally want to analyze tens or hundreds of petabytes of data – again with clear scientific benefits possible. The informal experience of many computer professionals holds up this idea as well – when an institution goes through a major system upgrade, demand for cyberinfrastructure resources can increase more than the actual increase in capability of the cyberinfrastructure. The Jevons Paradox is important generally in understanding trends in supply and demand in cyberinfrastructure, but in particular suggests that treating cyberinfrastructure like electricity, as suggested in St. Arnaud [110], is not in keeping with the goals and aspirations of the US research community nor in keeping with the best interests of the US and world societies that benefit from this research.

Budgeting for Cyberinfrastructure at University of Massachusetts Boston

The University of Massachusetts (UMass) Boston is a "small/medium" research institution, with an enrollment of 15,000 students and research funding of $50 million annually. UMass Boston established a committee on research and graduate studies to create a vision and recommend goals for a comprehensive plan to enhance the research enterprise, a vital part of its urban mission. In 2007, the committee recommended improving a number of support services, including enhanced network bandwidth for data-intensive activities, expansion of central data storage, and increased support for multiple operating systems. In 2008, four working groups prepared more detailed reports about specific research clusters the university wanted to emphasize: urban health and public policy, STEM education, computational sciences, and developmental sciences. These two sets of reports provided the IT unit with a better understanding of the university's overall research strategy and a starting point for developing a five-year plan to meet research needs. Having a written plan gave CIO Anne Agee a vehicle for discussion and a structure for making budget requests to implement the plan.

Figure E. UMass Boston Data Center Before Upgrade (from [129])

Figure F. UMass Boston Data Center After Upgrade (from [129])

UMass Boston prioritized use of its funds in a way that enabled implementation of a data center upgrade and added caged collocation space where researchers could house servers in a secure and reliable environment.

At UMass Boston, collaboration and the backing of the vice provost for IT and the vice provost for research have been key to enhancing research support. CIO Agee has worked with the CIOs of the other UMass institutions to facilitate collaborative efforts within the system to provide better support for all UMass researchers. Several UMass schools are jointly developing a virtual computing lab infrastructure that they can leverage to provide enhanced computing resources to researchers as well as better access to computing resources for students and faculty. Additionally, UMass Boston joined a consortium of Boston-area higher education and health care institutions to facilitate data sharing and collaboration among biomedical researchers. Finally, the UMass system joined forces with other Massachusetts institutions to develop a regional high-performance computing center that has the potential to provide enhanced resources for the smaller institutions in the consortium.

This information about UMass Boston and these photographs are excerpted, with permission, from Agee et al. [129]. This text and these photographs are licensed under the Creative Commons Attribution-Noncommercial-No Derivative Works 3.0 license [20].

9. Comments on and reinforcement of recommendations made by other ACCI task forces

The six ACCI Task Forces have developed their reports over the course of two years, with considerable interaction among task force members through cross-representation in task force activities, attendance at workshops, and exchange of ideas at ACCI meetings. It is thus no surprise that there is a great deal of consonance among the recommendations in the six task force reports. The Task Force on Campus Bridging in general supports and endorses the recommendations of all of the task forces. The most important overlap between concerns of the Task Force on Campus Bridging and the other five task forces is in the area of human resources and the creation of a 21st century knowledge workforce. As such, the Task Force on Campus Bridging specifically endorses the following recommendations of the Task Force on Cyberlearning and Workforce Development [11]:

> *We recommend that the NSF support research on methods for attracting and retaining a diverse STEM workforce.*
>
> *We recommend the creation of Cyberinfrastructure Institutes (CII) of academic, industry, nonprofit, and government partners working together to develop sustainable cyberlearning, broadening participation, interdisciplinary computational and data intensive science and engineering curricula as well as computational thinking programs and campus infrastructure in support of research and education. The campus infrastructure would include the shared hiring and training of staff and faculty and the sharing of knowledge to build and maintain the workforce of skilled programmers, systems staff, and user support staff needed to sustain the national CI enterprise including supercomputing resources, and provide a pathway for skilled practitioners for U.S. academia, industry, and government.*
>
> *We recommend that the NSF strengthen and bolster its national leadership in broadening participation toward the elimination of underrepresentation of women, persons with disabilities, and minorities.*
>
> *We recommend meaningfully involving Minority-Serving Institutions (MSIs) by enhancing their capacity as efficient and effective mechanisms for significantly engaging underrepresented minorities in STEM.*
>
> *We recommend establishing a Hispanic-Serving Institutions Program (HSIP) and augmenting two important NSF programs that have been extremely important to their respective target institutions—the Historically Black Colleges and Universities Undergraduate Program (HBCU-UP) and the Tribal Colleges and Universities Program (TCUP).*

The Task Force's discussion of human resources and the workforce of tomorrow has been aided by the position paper written by Brian D. Voss, Louisiana State University [193]. The definition of cyberinfrastructure presented near the beginning of this report makes clear that people are an essential component of cyberinfrastructure. Voss's position paper focuses on this "***role of people*** in the full and complete definition of cyberinfrastructure" – which Voss refers to as humanware. Voss states specifically that:

Time and again, at all levels of the acquisition and deployment of information technology through the past several decades, we have seen that without this humanware component – the people who make all the other components work – investments made in those other components – however significant in amounts! – do not realize their full potential without attention to and investment in the support of their use by scholars. Scholarly productivity and knowledge breakthroughs and discovery, however enhanced they may be by advanced cyberinfrastructure do not reach their full potential without (to steal a phrase from a current commercial) "the human element."

Implicit in many of the recommendations in this report, and in reports of the other ACCI Task Forces, is that long-term funding continuity for major and important projects is critical in part because of its impact on the workforce. The corrosive effects of uncertainty when staff are funded on short-term grant awards (two or three years at a time) has been noted over and over. Thus, we here note explicitly that a critical part of NSF and university support for cyberinfrastructure and campus bridging activities must be support for this "humanware" aspect of cyberinfrastructure. If we are as a nation to retain, within the fields of cyberinfrastructure and computational and data-enabled science and engineering, the best and brightest experts then the value proposition they face as individuals must be such that it is rational, and consistent with a good quality of life, to pursue and maintain a career in these fields. Recommendations consistent with this general view are made in many of the other Task Force reports.

The Task Force on Campus Bridging notes and particularly supports the following recommendations of the ACCI Task Force on High Performance Computing [10] and the ACCI Task Force on Grand Challenges [7]:

High Performance Computing:

> *[The NSF should] Develop a sustainable model to provide the academic research community with access, by 2015–2016, to a rich mix of HPC systems that:*
>
> *– deliver sustained performance of 20–100 petaflops on a broad range of science and engineering applications;*
>
> *– are integrated into a comprehensive national CI environment; and*
>
> *– are supported at national, regional, and/or campus levels.*
>
> *[The NSF should] Broaden outreach to improve the preparation of HPC researchers and to engage industry, decision-makers, and new user communities in the use of HPC as a valuable tool.*

Grand Challenges:

> *It is recommended that NSF, through OCI, continue to give high priority to funding a sustained and diverse set of HPC and innovative equipment resources to support the wide range of needs within the research community. These needs include support for the development of technologies to meet the foremost challenges in HPC, such as power-*

aware and application-sensitive architectures, new numerical algorithms to efficiently use petascale and exascale architectures, and data flow and data analysis at the extreme scale.

It is recommended that NSF:

1. 1) Support the creation of reliable, robust science and engineering applications and data analysis and visualization applications for Grand Challenges as well as the software development environment needed to create these applications.
2. 2) Provide support for the professional staff needed to create, maintain, evolve and disseminate the above applications as part of its grant funding.
3. 3) Establish best practices for the release of science and engineering applications and data as well as the workflows involved in their creation to ensure the reproducibility of computational results.

NSF should support education, training, and workforce development through the following grants and new programs:

1. 1) Educational excellence grants at the undergraduate and graduate levels, which include funding for the development of new courses, curricula, and academic programs in CS&E that address the computational and analytical skills required in virtually all STEM disciplines.
2. 2) Support for the formation of virtual communities engaged in CS&E education, including virtual entities leveraging expertise across colleges, universities, national and government laboratories, and supercomputing centers. Training, in the form of short courses, in core skills at all levels should be available online and supported 24/7, making the training broadly accessible.
3. 3) Institution-based traineeship grants that train graduate students and postdoctoral fellows in the multidisciplinary, team-oriented iteration among experiment, theory, and computation that is rapidly becoming a paradigm in critical STEM research areas and that has long been a standard in government laboratories and industry.
4. 4) The creation of a pan-agency facility or program to coordinate training in CS&E education.
5. 5) Grants that facilitate the transition of exceptionally talented graduate and postdoctoral students in computational science and engineering to permanent positions in academia as well as industry and government/national labs.
6. 6) Sustainable, permanent programs in CS&E research and education at all funding agencies to demonstrate a long-term commitment to supporting CS&E as a discipline, thereby creating reliable partners for universities seeking institutional transformational change and for trained workers seeking careers in CS&E.

The NSF should initiate a thorough study outlining best practices, barriers, success stories, and failures, on how collaborative interdisciplinary research is done among diverse groups involved in Grand Challenge projects.

The NSF should invest in research on virtual organizations that includes:

1. 1) Studying collaboration, including virtual organizations, as a science in its own right;
2. 2) Connecting smaller virtual organizations to large-scale infrastructure by providing supplementary funds to such projects, supporting development of tools, applications, services, etc. with a mandate to disseminate those elements to other communities and users;
3. 3) Investing in systematic, rigorous, project-level and program-level evaluations to determine the benefits from virtual organizations for scientific and engineering productivity and innovation;
4. 4) Encouraging NSF program officers to share information and ideas related to virtual organizations with training and online management tools.

Having called out these several recommendations for particular support, the Task Force on Campus Bridging makes a very few specific observations. It is a rational (if not altogether satisfactory) expectation that a large fraction of the research faculty of tomorrow will come from the research campuses of today. However, as noted in one of the recommendations above, there is a tremendous need for trained, professional staff. New NSF policies regarding postdoctoral mentoring plans will likely have as a side effect a decrease in the use of the title 'postdoctoral fellow' and increases in ranks of research faculty, permanent research staff positions, and professional staff supporting cyberinfrastructure. (The NSF guidance about postdoctoral mentoring plans does not specifically create any limits on the time one may be a postdoctoral fellow but does call for mentoring plans to identify steps that a mentor will take to enable a postdoctoral fellow to move into a faculty position. After a person has been a postdoctoral fellow for several years, "this time for sure" becomes an increasingly less credible claim about moving a person into a faculty position.)

The Task Force on Campus Bridging believes that small four-year campuses constitute a prime and greatly underutilized source of talent that can be educated and cultivated to form a large and important part of a highly talented and skilled 21st century workforce, particularly the professional and academic research component of such a workforce.

Education in computational and data-enabled science and engineering is a tremendous challenge at smaller institutions. While the basic principles in this area may persist for some time, the underlying cyberinfrastructure changes so rapidly that any curriculum involving practical use of CI must be updated once every two to three years in order to be up to date. Release time for faculty to create and update curriculum at most smaller schools is very scarce. MIT's release of engineering curriculum materials for use throughout the US revolutionized education in engineering [194]. There is a draft undergraduate curriculum for parallel and distributed computing [195]. However, there does not yet exist a general and widely accepted curriculum for computational and data-enabled science and engineering, nor for cyberinfrastructure software. The Task Force on Campus Bridging makes the following tactical recommendation, which is a generalization of a recommendation made in a prior NSF workshop report [151]:

> *Tactical Recommendation to the NSF #3: The NSF should support joint efforts with organizations such as the Association for Computing Machinery (ACM), the IEEE Computer Society, and/or Computing Research Association (CRA), to develop and maintain curriculum materials for undergraduate education in computer science and computational and data-enabled science and engineering.*

The ACCI Task Force on Campus Bridging supports the concepts for a national platform for cyberlearning as suggested in the report of the Task Force on Cyberlearning and Workforce Development [11]. However, we note that this vision requires network access that is as of yet a vision, not a reality, for many small campuses throughout the US. However, efforts such as the Little Fe project [196] provide a parallel computing environment that can be run locally, at any institution regardless of networking capability, for under $5,000. This means that availability of curriculum material is in practice one of the primary obstacles standing between hundreds of thousands of students at smaller colleges and universities and an education that would prepare them to be part of a highly skilled 21st century workforce that understands and has practical experience in parallel computing in particular and computational and data-intensive science and engineering in general.

Reinforcing comments made earlier, the development – under NSF guidance – of a national cyberinfrastructure blueprint would aid the development of curriculum materials that would be particularly useful for faculty and staff at MSIs and smaller universities and colleges generally.

10. Closing thoughts on transformative research, pressing scientific and societal needs, US global competitiveness, and campus bridging

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The NSF, in its focus on transformative research, is reacting to both recommendations from the National Science Board [197, 198] and pressing societal needs. In considering the concept of transformative research one must naturally go back to Thomas Kuhn's seminal work "The structure of scientific revolutions." What Kuhn got right, and where he made errors of fact or interpretation, is still a subject of active research in the history and philosophy of science. As pointed out by Kuhn in a postscript to the third edition of "The structure of scientific revolutions" (and many others in other places), Kuhn used the word 'paradigm' in a variety of sometimes conflicting senses [199]. One sense of this – referring to the overall sense of the state of knowledge in a given discipline or subdiscipline – he terms the "disciplinary matrix." In general, it seems unrealistic to think that every single investigator research project funded by the NSF is going to change the disciplinary matrix and overturn our current overall state of understanding about the world around us. Advances in string theory are not going to alter our basic understanding of DNA as the primary repository of genetic information in most forms of life as we know them on earth (nor our understanding of the deviations from DNA in this role where they exist).

However, in the more restrictive sense of 'paradigm' as a particular scientific concept or related set of theories, we see many signs that there are significant and transformative changes possible. It is indeed in that sense that the NSF discusses transformative research, including the following definition adopted by the NSF:

> *"Transformative research involves ideas, discoveries, or tools that radically change our understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education. Such research challenges current understanding or provides pathways to new frontiers." [200]*

Kuhn talks about changes in instrumentation and community feelings that evidence was accumulating in ways that were difficult to interpret with current theory as signs of impending paradigm change. The NSF offers many examples of transformative research accomplishments from the past [198], and many of those transformative research accomplishments relate directly to the development of new instruments or technologies. Changes in cyberinfrastructure may constitute a fundamental change in the instruments available to the scientific community, and the alignment of scientific research activities within Virtual Organizations may constitute a fundamental change in the use of those instruments. And there are signs, at least, of community belief that either certain current paradigms or that our collective ability to implement those paradigms and theories they include within computer simulations and data analyses are not adequate.

The impact of global warming is one such area of debate. These scientific debates have now more importance than ever before for the US and global societies. There are serious concerns about tipping points in the global environment and the ability of the growing human population to live in a fashion we would want for ourselves or for future generations. These are hard, serious problems and the US science and engineering research community should be considering them carefully. Carrying out the recommendations contained in this report will not in and of itself save the earth (or its inhabitants). However, we may, as a country and a global human population, be at a tipping point that is irreversible. It is thus a critical responsibility of the scientific community to as best possible apply the cyberinfrastructure we have and develop new cyberinfrastructure that aids transformative research, enabling understanding of the world around us and the impact on it of our activities. Beyond the particular issue of the global environment, making the best possible use of the overall national cyberinfrastructure, and advancing the capacity and capabilities of that cyberinfrastructure, will aid the US generally in terms of global competitiveness, quality of life, and ability to serve as a model and leader of other counties.

Investment and leadership by the NSF in technologies related to cyberinfrastructure – and effective actions by the US science and engineering research and education community – can enable more effective campus bridging to facilitate fundamental changes that result in research breakthroughs. To be most valuable, such changes must affect the way research and education are organized – from campus cyberinfrastructure and campus bridging to national cyberinfrastructure, NSF funding strategies, and academic reward systems. These tasks are definitely not the low hanging fruit – but they may be the most important and best fruit and thus should be our focus as a community.

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Appendix 1. Task Force membership

Task Force members

Craig Stewart
Task Force on Campus Bridging Chair
Executive Director, Pervasive Technology Institute; Associate Dean, Research Technologies
Office of the Vice President for Information Technology & CIO
Indiana University
601 East Kirkwood Avenue
Bloomington, IN 47405
stewart@iu.edu

Guy Almes
Task Force on Campus Bridging Co-Chair
Director, Academy for Advanced Telecommunications and Learning Technologies
Texas A&M University
612 Blocker Building
3139 TAMU
College Station, TX 77843-3143
galmes@tamu.edu

Jim Bottum
Task Force on Campus Bridging Co-Chair
Chief Information Officer and Vice Provost for Computing & Information Technology
Clemson University
209 Sikes Hall
Clemson, SC 29634
jb@clemson.edu

Gary Crane
Director of IT Initiatives
Southeastern Universities Research Association (SURA)
1211 Alderman Road
Palmyra, NY 14522
gcrane@sura.org

Patrick Dreher
Chief Domain Scientist for Cloud Computing
Renaissance Computing Institute
100 Europa Drive Suite 540
Chapel Hill, North Carolina 27517
dreher@renci.org

Gerald Giraud
Vice President for Instruction
Oglala Lakota College
490 Piya Wiconi Rd
Kyle, SD 57752
ggiraud@olc.edu

Andrew Grimshaw
Professor of Computer Science
Department of Computer Science
School of Engineering and Applied Science
University of Virginia
P.O. Box 400740
Charlottesville, Virginia 22904-4740
grimshaw@cs.virginia.edu

Sandra Harpole
Professor, Physics Education
Mississippi State University
237 Hilbun Hall
P.O. Drawer 5167
Mississippi State, MS 39762
sharpole@ra.msstate.edu

Dave Jent
Office of the Vice President for Information Technology & CIO
Indiana University
601 East Kirkwood Avenue
Bloomington, IN 47405
djent@iu.edu

Ken Klingenstein
Senior Director, Internet2 Middleware & Security
8454 Boulder Hills Dr
Longmont, CO 80517
kjk@internet2.edu

Miron Livny
Director of Core Computational Technology
University of Wisconsin
1210 W. Dayton St.
Madison, WI 53706-1685
miron@cs.wisc.edu

Lyle Long
Director, Computational Science Graduate Minor Program
Pennsylvania State University
229 Hammond Building
University Park, PA 16802
lnl@psu.edu

Clifford A. Lynch
Executive Director, Coalition for Networked Information
21 Dupont Circle
Washington, DC 20036
clifford@cni.org

D. Scott McCaulay
Indiana University Pervasive Technology Institute
2719 East 10th Street
Bloomington, IN 47408
smccaula@indiana.edu

John McGee
Director of Cyberinfrastructure
Renaissance Computing Institute
100 Europa Drive Suite 540
Chapel Hill, North Carolina 27517
mcgee@renci.org

Michael R. Mundrane
Deputy Chief Information Officer
University of California, Berkeley
2195 Hearst, Room 200JA
Berkeley, CA 94720
mundrane@berkeley.edu

Jan Odegard
Executive Director, Ken Kennedy Institute for Information Technology
Rice University
P.O. Box 1892
Houston, Texas 77251-1892
odegard@rice.edu

James Pepin
Chief Technology Officer
Clemson University
340 Computer Court
Anderson, SC 29625
pepin@clemson.edu

James Rice
Professor/Department Head/SD EPSCoR Director
South Dakota State University
Chemistry-Biochemistry
Post Office Box 2202
Brookings, SD 57007
James.Rice@sdstate.edu

Larry Smarr
Director
Harry E. Gruber Professor
Computer Science and Information Technologies
Jacobs School of Engineering
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093-0436
lsmarr@ucsd.edu

Brian Voss
Vice Chancellor for Information Technology
Information Technology Services
Louisiana State University
200 Frey Computing Services
Baton Rouge, LA 70803
cio@lsu.edu

Von Welch
Indiana University Pervasive Technology Institute
2719 East 10th Street
Bloomington, Indiana 47408
vwelch@indiana.edu

Ex Officio member of the task force:
Dale Lantrip (formerly of Indiana University)

NSF Liaisons to the task force

Alan Blatecky
Head, National Science Foundation Office of Cyberinfrastructure
4201 Wilson Boulevard, Room 1145S
Arlington, VA 22230
ablateck@nsf.gov

Manish Parashar
Program Director, National Science Foundation Office of Cyberinfrastructure
628 CoRE
Department of Electrical & Computer Engineering
Rutgers University
94 Brett Road
Piscataway, NJ 08854-8058
parashar@ece.rutgers.edu

Robert Pennington
Program Director, National Science Foundation
4201 Wilson Blvd., Room 1145 S
Arlington, VA 22230
rpenning@nsf.gov

Jennifer Schopf
Program Officer, National Science Foundation Office of Cyberinfrastructure
4201 Wilson Blvd., Room 940 S
Arlington, VA 22230
jschopf@nsf.gov

Appendix 2. Campus Bridging: Networking & Data-centric Issues Workshop

Workshop web site

http://pti.iu.edu/campusbridging/networking/

Position papers

All position papers are available from the workshop web site.

Title	Author(s)
The OptIPortal, a Scalable Visualization, Storage, and Computing Termination Device for High Bandwidth Campus Bridging	Thomas A. Defanti; Jason Leigh; Luc Renambot; Byungil Jeong; Alan Verlo; Lance Long; Maxine Brown; Dan Sandin; Venkatram Vishwanath; Qian Liu; Mason Katz; Phil Papadopoulous; Joseph Keefe; Greg Hidley; Greg Dawe; Ian Kaufman; Bryan Glogowski; Kai-Uwe Doerr; Javier Girado; Jurgen P. Schulze; Falko Kuester; Larry Smarr
A High-Performance Campus-Scale Cyberinfrastructure For Effectively Bridging End-User Laboratories to Data-Intensive Sources	Philip Papadopoulous; Larry Smarr
Regional Cyberinfrastructure as a Bridge Between Campus and National CI	Greg Monaco; Rick McMullen
The Role of a Data-Intensive Network (DIN)	Willis Marti; Guy Almes
A Strategy for Campus Bridging for Data Logistics	Terry Moore
Extending Cyberinfrastructure Beyond Its Own Boundaries -- Campus Champion Program	S. Kay Hunt; Scott Lathrop
Attributes, Authorization and Cyberinfrastructure	Ken Klingenstein
Realizing a National Cyberinfrastructure via Federation	Andrew Grimshaw
Why is Advanced Cyberinfrastructure Not More Widely Used?	Russ Hobby
OSG Campus Grid Working Meeting Notes	Brian Bockelman; Dan Bradley; Keith Chadwick; Steve Gallo; Sebastien Goasguen; Rob Gardner; Sam Hoover; John McGee; Doug Olson; Preston Smith; Ben Cotton; Prakashan Korambath
Data Approaches for Campus Bridging	Michael Shoffner; Ilia Baldine; Leesa Brieger; Jason Coposky; Kevin Gamiel; Jefferson Heard; Howard Lander; Anirban Mandal; John McGee; Nassib Nassar; Arcot Rajasekar; Charles Schmitt; Erik Scott; Michael Stealey; Stanley Ahalt
Enabling and Sustaining Campus-to-Campus Cyberinfrastructure	Gary Crane; John-Paul Robinson; Phil Smith

Workshop Attendees

Mike Abbiatti, Arkansas Research and Education Optical Network
Guy Almes, Texas A&M University*
Alan Blatecky, National Science Foundation
Grover Browning, Indiana University
Marianne Chitwood, I-Light
Steve Corbato, University of Utah
Gary Crane, Southeastern Universities Research Association*
Matt Davy, Indiana University
Ray Ford, University of Montana
Jim French, University of Virginia
Rob Gardner, University of Chicago
Brandon George, University of Oklahoma
Andrew Grimshaw, University of Virginia*
Victor Hazelwood, University of Tennessee Knoxville
Russ Hobby, Internet2
Kay Hunt, Purdue
Dave Jent, Indiana University*
Ken Klingenstein, Internet2*
Dale Lantrip, Indiana University
Scott Lathrop, Argonne National Laboratory
Jim Leous, Penn State
Akhtar Mahmood, Bellarmine
John McGee, Renaissance Computing Institute*
Susan Mehringer, Cornell
Greg Monaco, Great Plains Network
Richard Moore, San Diego Supercomputing Center / University of California San Diego
Michael R. Mundrane, University of California Berkeley*
Radha Nandkumar, National Center for Supercomputing Applications
Jan Odegard, Rice University*
Jim Pepin, Clemson University*
Ruth Pordes, Fermilab
Kurt Seiffert, Indiana University
Michael Shoffner, University of North Carolina
Steve Simms, Indiana University
Larry Smarr, California Institute for Telecommunications and Information Technology*
Craig Stewart, Indiana University*
Craig Struble, Marquette
Martin Swany, University of Delaware
David Todd, University of Vermont
John Towns, NCSA
Rob Vietzke, Internet2
James Vincent, University of Vermont
Von Welch, Independent*
Matt Zekaukas, Internet2
Tom Zeller, Indiana University

* Indicates Task Force on Campus Bridging member

Local Workshop Help and Technical Assistance

Amy Bennion, University of California San Diego
Billiekai Boughton, San Diego Supercomputing Center / University of California San Diego
Diane B. Didier, Arkansas Research and Education Optical Network
Clarissa Fermin, University of California Berkeley
Carla Harris, Texas A&M University
Rudeana Honeycutt, Indiana University
Kristen Johnson, University of California San Diego
Dale Lantrip, Pervasive Technology Institute, Indiana University
Peg Lindenlaub, Pervasive Technology Institute, Indiana University
Jemise Lockhart, Fermilab
Therese Miller, Pervasive Technology Institute, Indiana University

Appendix 3. Campus Bridging: Software & Software Service Issues Workshop

Workshop web site

http://pti.iu.edu/campusbridging/software/

Position papers

Title	Author(s)
Campus Bridging as an Exercise in Cultural Bridging	Dan Fraser
Barriers to Inter-Campus Cyberinfrastructure	John-Paul Robinson
Position Paper on Campus Bridging Software and Software Service Issues	Rion Dooley
Bridging Resources Using Lustre as a Wide Area Filesystem	Stephen Simms

Workshop attendees

Guy Almes, Texas A&M University*
William Barnett, Indiana University
David Chaffin, University of Arkansas
Tom Cheatham, University of Utah
Gary Crane, Southeastern Universities Research Association*
Kim Dillman, Purdue University
Dan Fraser, Open Science Grid
Brandon George, University of Oklahoma
Andrew Grimshaw, University of Virginia*
Gary Jung, Lawrence Berkeley National Laboratory
Rajendar Kanukanti, Louisiana Optical Network Initiative
Daniel S. Katz, University of Chicago/TeraGrid
Ken Klingenstein, Internet2*
Bill Labate, University of California Los Angeles
Dale Lantrip, Indiana University
Cliff Lynch, Coalition for Networked Information *
Miron Livny, University of Wisconsin*
Man Luo, University of North Carolina
John McGee, Renaissance Computing Institute*
Amit Majumdar, San Diego Supercomputing Center / University of California San Diego / TeraGrid
Jonathan Morrison, Indiana University
Michael Mundrane, University of California Berkeley*
Jan Odegard, Rice University*
Vani Panguluri, Southern University
Jim Pepin, Clemson University*
John-Paul Robinson, University of Alabama-Birmingham / Southeastern Universities Research Association
Traci Ruthkoski, University of Michigan
Ray Sheppard, Indiana University
Steve Simms, Indiana University
Martin Swany, University of Delaware
David Walker, UC-Davis
Von Welch, Independent*

* Indicates Task Force on Campus Bridging member

Technical Assistance

Dale Lantrip (Indiana University) handled logistics for the workshop.

Appendix 4. Campus Bridging: Campus Leadership Engagement in Building a Coherent Campus Cyberinfrastructure Workshop

Workshop web site

http://pti.iu.edu/campusbridging/leadership/

Workshop attendees

Guy Almes, Texas A&M University*
Fran Berman, Rensselaer Polytechnic Institute
Larry Conrad, University of North Carolina
James Davis, Iowa State University
James Davis, University of California Los Angeles
Maureen Dougherty, University of Southern California
Patrick Dreher, Renaissance Computing Institute
David Gift, Michigan State University
Gilbert Gonzales, University of New Mexico
Joel Hartman, University of Central Florida
James Hilton, University of Virginia
Bill Hogue, University of South Carolina
Greg Jackson, EDUCAUSE
Sally Jackson, University of Illinois at Urbana-Champaign
Klara Jelinkova, University of Chicago
Kamran Khan, Rice University
John Kolb, Rensselaer Polytechnic Institute
Karl Kowalski, University of Alaska, Fairbanks
David Lassner, University of Hawaii
Philip Long, Yale
John McGee, Renaissance Computing Institute*
Michael McPherson, University of Virginia
Michael Mundrane, University of California Berkeley*
Jan Odegard, Rice University*
Michael Pearce, University South Florida
Rob Pennington, National Science Foundation
Jim Pepin, Clemson University*
Michael Pickett, Brown University
Jim Rankin, University of Arkansas
Ilee Rhimes, University of Southern California
Tracy Schroeder, Boston University
Peter Siegel, University of California, Davis
Larry Smarr, California Institute for Telecommunications and Information Technology*
Joel Smith, Carnegie Mellon University
Donald Spicer, University System of Maryland
Craig Stewart, Indiana University*
David Walker, University of California Davis
Von Welch, Independent*
Brad Wheeler, Indiana University

* Indicates Task Force on Campus Bridging member

Local Workshop Help and Technical Assistance

Maureen Dougherty, University of Southern California

Appendix 5. ACCI Recommendation Letter for the Creation of a Program in Computational and Data-Enabled Science and Engineering

Dear Dr. Bement,

At the May 2010 meeting, the National Science Foundation Advisory Committee for Cyberinfrastructure unanimously endorsed the following recommendation:

> **The National Science Foundation should create a program in Computational and Data-Enabled Science and Engineering (CDS&E), based in and coordinated by the NSF Office of Cyberinfrastructure.**

The new program should be collaborative with relevant disciplinary programs in other NSF directorates and offices.

Computational and Data-Enabled Science and Engineering (CDS&E) is now clearly recognizable as a distinct intellectual and technological discipline lying at the intersection of applied mathematics, computer science, and core science and engineering disciplines. It is dedicated to the development and use of computational methods and data mining and management systems to enable scientific discovery and engineering innovation.

CDS&E builds on the area of Computational Science and Engineering, growing out of scientific computation and the explosion of production of digital data. We regard CDS&E as explicitly recognizing the importance of data-enabled, data-intensive, and data-centric science. CDS&E broadly interpreted now affects virtually every area of science and technology, revolutionizing the way science and engineering are done. Theory and experimentation have for centuries been regarded as two fundamental pillars of science. It is now widely recognized that computational and data-enabled science forms a critical third pillar. CDS&E includes new methodologies for science and engineering that are indispensible to the nation's welfare, competitiveness, and standing in the international scientific community and global economy.

Computational and Data-Enabled Science and Engineering (CDS&E) is fundamentally important to the long-term NSF strategic initiative called CF21: Cyberinfrastructure Framework for 21st Century Science and Engineering. The NSF CF21 vision calls for a "comprehensive plan for education and outreach in computational science to support learning and workforce development for 21st century science and engineering."

NSF can make a strong statement that will lead the Foundation, researchers it funds, and US universities and colleges generally, by recognizing Computational and Data-Enabled Science and Engineering as the distinct discipline it has clearly become.

Arden L. Bement, Jr. (signature) — 05/27/2010

Approved
Arden L. Bement, Jr.
Director
National Science Foundation

Date

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About the cover image

The cover image is based on Joachim Bering's etching of the city of Königsberg, Prussia as of 1651 (now Kaliningrad, Russia). Seven bridges connect two islands in the Pregal River and the portions of the city on the bank. The mathematical problem of the Seven Bridges of Königsberg is to find a path through the city that crosses each bridge once and only once. Euler proved in 1736 that no solution to this problem exists or could exist.

The goal of campus bridging is to enable the seamlessly integrated use among: a scientist's or engineer's personal cyberinfrastructure; cyberinfrastructure on the scientist's campus; cyberinfrastructure at other campuses; and cyberinfrastructure at the regional, national, and international levels; so that they all function as if they were proximate to the scientist. The challenges of effective bridging of campus cyberinfrastructure are real and challenging – but not insolvable if the US open science and engineering research community works together with focus on the greater good of the US and the global community. Other materials related to campus bridging may be found at: https://pti.iu.edu/campusbridging/

http://www.nsf.gov/od/oci/taskforces